Bulletin No. 59

Hydrogeological and geothermal regimes in the Phanerozoic succession, Cold Lake area, Alberta and Saskatchewan

Brian Hitchon, S. Bachu, C.M. Sauveplane, A. Ing, A.T. Lytviak, and J.R. Underschultz

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Cover:
Beaverhill Lake aquifer system hydrogeology. Top left: isopachs (m); Top right: salinity (mg/L) of formation waters; Bottom left: temperature distribution (°C); Bottom right: potentiometric surface (m).

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Abstract

The natural, steady-state fluid flow and geothermal regimes were determined for a region defined as Tp 50-70, R 15 W3M to R 17 W4M (60 000 km^2), including the Cold Lake Oil Sand Deposit and adjacent heavy oil areas to the south. The study was based on information from 14 800 wells, 1858 analyses of formation waters, 2155 drillstem tests, 46 700 core analyses, and 19 218 bottom-hole temperature measurements. Data processing was carried out using specially designed software developed by the Basin Analysis Group.

Regional geology was synthesized in terms of definable stratigraphic successions, and individual, lithologically distinct stratigraphic units were characterized by structure contour and isopach maps. The fluid flow and geothermal regimes for individual aquifers, aquitards, and aquicludes were described using isopach, salinity distribution, potentiometric surface and temperature distribution maps, together with pressure-head vs depth plots and hydraulic head cross sections. Based on this information the hydrostratigraphic units can be grouped into ten aquifers and aquifer systems (Lower Paleozoic, Winnipegosis, Beaverhill Lake, Camrose Tongue, Grosmont, Winterburn, McMurray, Clearwater, Mannville, and Viking), four aquitards and aquitard systems (Ireton, Clearwater, Joli Fou, and Colorado) and three aquicludes and aquiclude systems (Precambrian, Lower Devonian, and Prairie). Oil sand layers act as intermediate to weak aquitards, and lateral flow probably bypasses them.

Lateral flow is dominantly regional to the northeast in aquifers in the Lower Paleozoic and Middle Devonian. In the McMurray and Clearwater aquifers lateral flow is of the intermediate type to the west and northwest under the influence of a drain effect by the underlying Grosmont aquifer system. Lateral flow in the Mannville aquifer is indeterminate, being intermediate to local, while lateral flow in the Viking aquifer (within the Colorado aquitard system) is also intermediate to local, and topographically controlled.

Heat flow is mainly conductive, the convective component being negligible due to the low permeability of the rocks. The integral geothermal gradient is strongly dependent on the average thermal conductivity of the sedimentary column, which in turn depends on the lithology of the strata. As a result, the integral geothermal gradient is highest in the areas with a thick section of Ireton shale and lowest in regions where halite is present without overlying Ireton shale.

The synthesis of this vast amount of information on the natural fluid flow and geothermal regimes in the study area was carried out under a jointly funded contract between the Alberta Research Council and Alberta Environment in preparation for the evaluation of deep waste injection in the Cold Lake area.

Introduction

Initial discussions concerning a study of the hydrogeology of the Cold Lake region took place between the Alberta Research Council and Alberta Environment in early 1981. The primary concern of both parties was the then imminent development of large commercial in situ recovery operations in the Cold Lake Oil Sand Deposit, and the possible impact these operations might have on the natural flow systems, specifically on the nearsurface potable groundwater resources. There was mutual agreement that whatever study eventually evolved, the experience gained should be applicable to other oil sand deposits in Alberta. Because of the vast amount of data available, and required, for such a hydrogeological study (much of which was not in machine-readable form) one of the primary objectives had to be the entry and processing of information; the technology for data entry and processing, as well as the methods for synthesis of the hydrogeological and geothermal regimes were to be transferable to other oil sand deposits and required the development of a series of integrated software packages. Based on these software packages and the specific data entered for the Cold Lake region, a comprehensive study on the hydrogeology of that region could then be carried out. Because the primary concerns and approach to the problem were the same for both organizations it was agreed that the study be funded equally. The results of the initial three-year study included a contract report (Basin Analysis Group 1985) and a description of the techniques used to analyse fluid and heat regimes in sedimentary basins with large data bases (Bachu et al. 1987).

Following that study it was decided to investigate, through another jointly funded contract, the effects of deep waste disposal in the Cold Lake region. In order to include pilot and commercial operations in all major oil sand and heavy oil occurrences in the region which either practiced deep waste disposal or predicted the need for deep waste disposal in the future, it was necessary to expand the area of investigation. The study area was, therefore, made large enough to ensure both the adequate representation of the natural steady-state flow regime and the elimination of artificial boundary effects in the area selected for numerical simulation of deep waste injection.

This bulletin includes all information obtained during the two jointly funded contracts that relates to the natural steady-state fluid flow and geothermal

regimes. A second bulletin (Bachu et al. 1989) is concerned with the effects of deep waste injection. The initial contract report (Basin Analysis Group 1985) includes several appendices of raw and interpreted data for the smaller Alberta portion of the Cold Lake region. For the larger study area covered by this bulletin the data base is available only in electronic form. The Cold Lake study area is defined as Tp 50-70, R 15 W3M to R 17 W4M (figure 1). It straddles the Alberta-Saskatchewan border, and includes the entire Lower Cretaceous Cold Lake Oil Sand Deposit and the adjacent heavy oil region to the south, from Lindberg to the northern part of the Lloydminster field. The bulletin is presented in two sections: regional geology, and analysis of the natural fluid flow and geothermal regimes. An appendix presents the regional hydrodynamic information in tabular and graphical form, without comments. Standard SI units are used throughout this bulletin, including those for time.

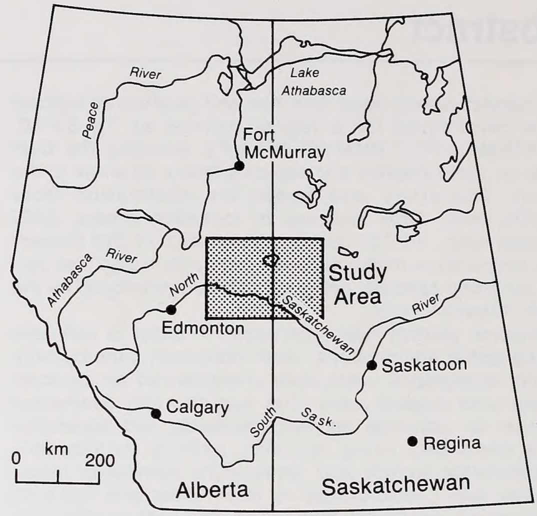


Figure 1. Cold Lake study area, Alberta and Saskatchewan.

Regional geology

Introduction

This section of the bulletin presents an overview of the Phanerozoic history of the Cold Lake region in the context of the major depositional and erosional events that have taken place in this part of the Western Canada Sedimentary Basin. The stratigraphic column is broken down into discrete sedimentary packages, each of which represents deposition in a distinct paleogeographic configuration with characteristic geometry and internal facies patterns. This provides the necessary background information fundamental to the hydrogeological portion of the study.

The two main sources of information used to generate regional geological maps for the Cold Lake study area were the well data files of the Alberta Energy Resources Conservation Board (ERCB), and Saskatchewan Energy and Mines. Variations in the amount and distribution of data throughout the stratigraphic column reflect the distribution of oil and gas reservoirs. In general, the amount of data increases dramatically for formations within the Upper Devonian and Cretaceous where most of the major oil and gas discoveries have been made. This bias is also reflected in the literature, where stratigraphic and sedimentological understanding is far greater for formations which have economic significance.

Reference was made to geophysical well logs for formations which are geologically more complex, and which required a greater degree of refinement. For example, the delineation of discontinuous, thin oil sand layers was done manually using a network of well log cross sections.

The geological synthesis of the study area is illustrated through a series of isopach and structure contour maps spanning from the Precambrian to the top of the bedrock. These maps were used to determine the geometry of this portion of the Western Canada Sedimentary Basin during various stages in its overall evolution. The stratigraphic nomenclature used in the study area is shown in table 1.

Western Canada Sedimentary Basin

The Western Canada Sedimentary Basin is a westward-thickening wedge of sedimentary strata which attains a maximum thickness of more than 6 km in the axis of the Alberta Syncline (figure 2). It extends southwest from a zero edge at the Canadian Shield outcrop to a maximum thickness at the front of the Cordilleran Foreland Thrust Belt. Regional dips range from 5 to 10 m/km. Publications by McCrossan and Glaister (1964), Parsons (1973), and Porter et al. (1982) provide good overall reviews of the geological history of the basin.

The geological history of the Western Canada Sedimentary Basin is linked to two fundamentally different tectonic settings. The initial platformal phase involved transgressive onlap of the Precambrian crystalline basement of the North American craton and the development of epeirogenic arches and basins on the cratonic platform (Porter et al. 1982). It coincides with the deposition of Late Proterozoic to Jurassic sediments and is dominated by shallow water carbonates and evaporite sequences.

During the Late Jurassic to Paleocene interval, allocthonous oceanic terranes were accreted to the western margin of North America. The continental terrace wedge was compressed, detached from its base-

Table 1. Generalized stratigraphic nomenclature.

Stratigraphic nomenclature						
Eon	Era	Period		Group	Formation	Sequence
Phanerozoic	Cenozoic	Tertiary				
	Mesozoic	Cretaceous	U	Belly River		Post-Colorado
					Lea Park	Post-Colorado
				Colorado	1WS	Colorado
					Fish Scales	
					Viking / St. Walburg	
					Joli Fou / Spinney Hill	
			L	Mannville	Grand Rapids	Mannville
					Clearwater	
					Cummings/ Wabiskaw	
					McMurray	
		Jurassic		Not deposited?		
		Triassic		Not deposited		
	Paleozoic	Permian		Not deposited		
		Pennsylvanian		Not deposited		
		Mississippian				
		Devonian	U	Wabamun		
				Winterburn		
				Woodbend	Grosmont / Camrose	Upper Devonian
					Ireton / Leduc	
					Cooking Lake	
				Beaverhill Lake		
			M	Elk Point	Watt Mountain	Middle Devonian
					Prairie	
					Winnipegosis	
					Contact Rapids	
			L		Cold Lake	Lower Devonian
					Ernestina Lake	
					Lotsberg	
					Basal Red Beds	
				Not deposited		
		Silurian				
		Ordovician			Red River	Ordovician
		Cambrian	U		Deadwood	Cambrian
			M		Earlie	
					Basal Sandstone	
			L	Not deposited		
Proterozoic	Hadrynian					
	Helikian					
	Aphebian					
	Archaean					

Absent from study area

Figure 2. Total preserved thickness of Phanerozoic rocks east of the Cordilleran Foreland Thrust Belt (after Porter et al. 1982).

ment, and thrust over the flank of the craton to form the present eastern part of the Cordillera (Porter et al. 1982). The continental lithosphere responded to the tectonic loading by isostatic flexure, initiating the development of a foreland basin to the east. The sediments that filled the foreland basin comprise clastic detritus shed by the evolving Cordillera.

Basin analysis

The regional geology of the Cold Lake study area is discussed in terms of successions representing deposition during different configurations of the Western Canada Sedimentary Basin through time (table 1). As discussed earlier, this is done in two parts, corresponding to the two major tectonic regimes which controlled deposition in the basin.

Development of the passive continental margin succession

Precambrian basement

The Precambrian continental craton, which forms the basement of the Western Canada Sedimentary Basin, consists mainly of Archaean crystalline rocks and Aphebian (2500-1750 Ma) supracrustal rocks that were modified by deformation, metamorphism, and magmatism during the early Proterozoic (1750 Ma) Hudsonian orogeny. These rocks are exposed in the Churchill Province of the Canadian Shield (Porter et al. 1982) and have a strong northeast-southwest structural trend. The parallel orientation of some of the cratonic arches, such as the Peace River Arch, suggests that this structural grain continues into the subsurface. In the Cold Lake study area, the Precambrian basement dips gently toward the southwest (figure 3a).

Cambrian

The first succession, comprising Middle to Upper Cambrian strata, marks the beginning of the Phanerozoic record of deposition on the cratonic platform. Unlike much of the later Phanerozoic, the pattern of sedimentation was not influenced by vertical movement of cratonic arches. The sea trangressed eastward and deposited a basal quartz sand over the entire western flank of the craton (Pugh 1973). This basal sandstone unit is derived from the Precambrian basement, and becomes progressively younger toward the east. An isopach map of the Basal Cambrian sandstone (figure 3b) reflects the uneven thickness of the unit; substantial thickening occurs in the southeast portion of the study area, whereas the sandstone is significantly thinner in the vicinity of Tp 60, R 16, W4M. The Basal Cambrian sandstone thins northward, with the approximate zero edge located between Tp 65-70.

North of this erosional edge is Granite Wash. Mapping the Granite Wash using geophysical well logs posed a number of problems. Although it is a reworked sand deposit, it exhibits a high gamma ray response on the well logs, making it indistinguishable from shaley deposits. In addition, due to the lack of well control in the northern portion of the study area, it is difficult to resolve whether the Granite Wash is actually present, whether it is porous and permeable, or whether it is in contact with the Basal Cambrian sandstone.

With continued transgressions, the basal sand gave way to a series of shallowing upward cycles. Each cycle consists of shale at the base, grading upward into carbonate rocks. Laterally, three broad facies belts can be recognized: an inner shoreline detrital belt, a middle carbonate belt, and an outer detrital belt. The study area is situated in the inner shoreline detrital belt where there is a high proportion of shale, siltstone and sandstone (Pugh 1973), representing detritus eroded from the Precambrian craton. Cambrian rocks above the Basal Sandstone in the Cold Lake study area are represented by a series of glauconitic siltstones and shales of the Earlie and Deadwood Formations. Figure 4a is a structure contour map on the top of the Cambrian and figure 4b shows the total thickness of the Cambrian in the study area.

Following the accumulation of the Cambrian succession, the Western Canada Sedimentary Basin was affected by a pre-Middle Ordovician episode of uplift and erosional bevelling. The regional eastward bevelling marked a relatively uniform westward tilt of the craton. Cratonic arches and basins also developed at this time and had a profound influence on patterns of subsequent sedimentation (figure 5).

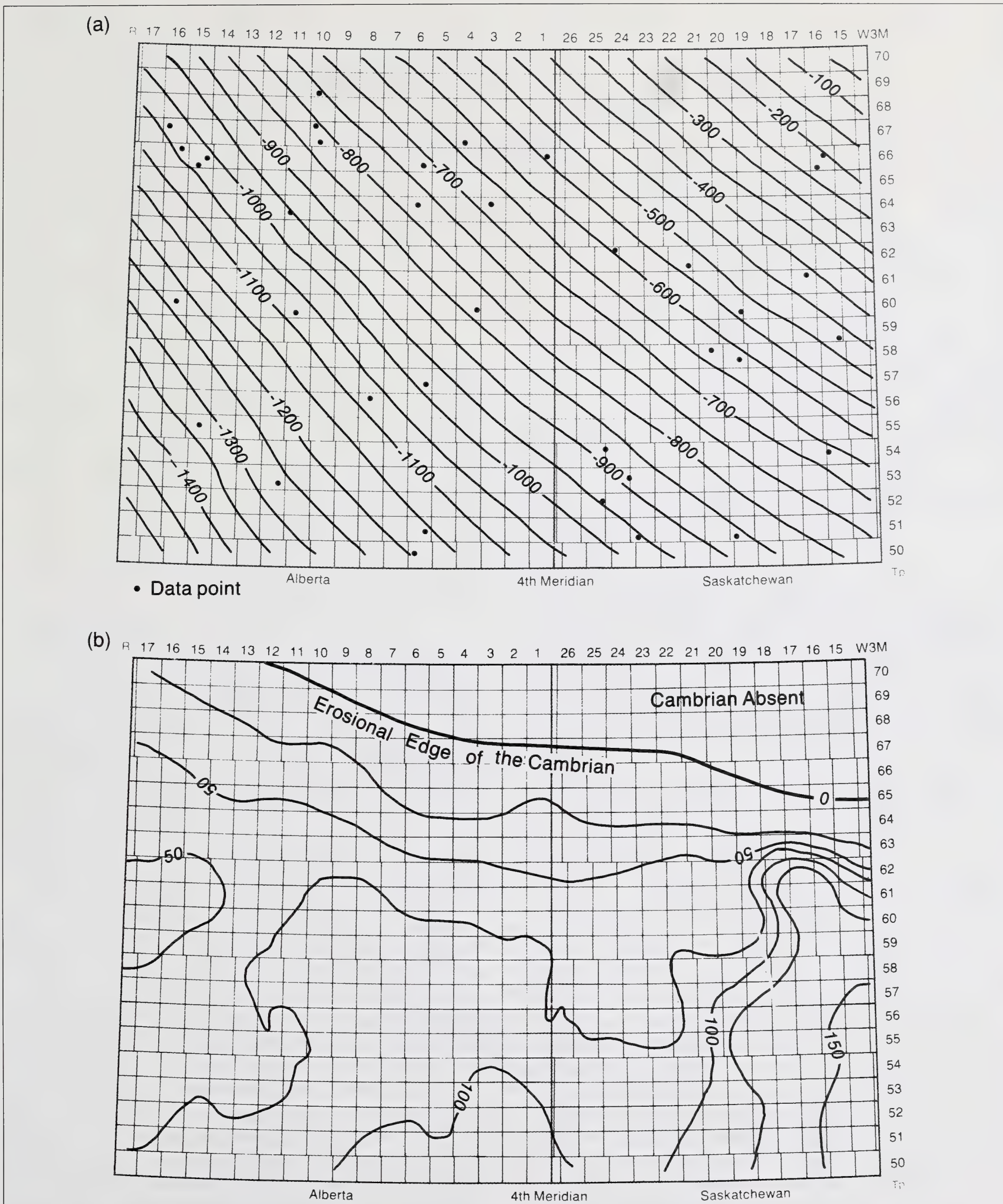


Figure 3. (a) Structure contour map of the Precambrian surface (contour interval 50 m); (b) Isopach map of the Basal Cambrian sandstone (contour interval 25 m).

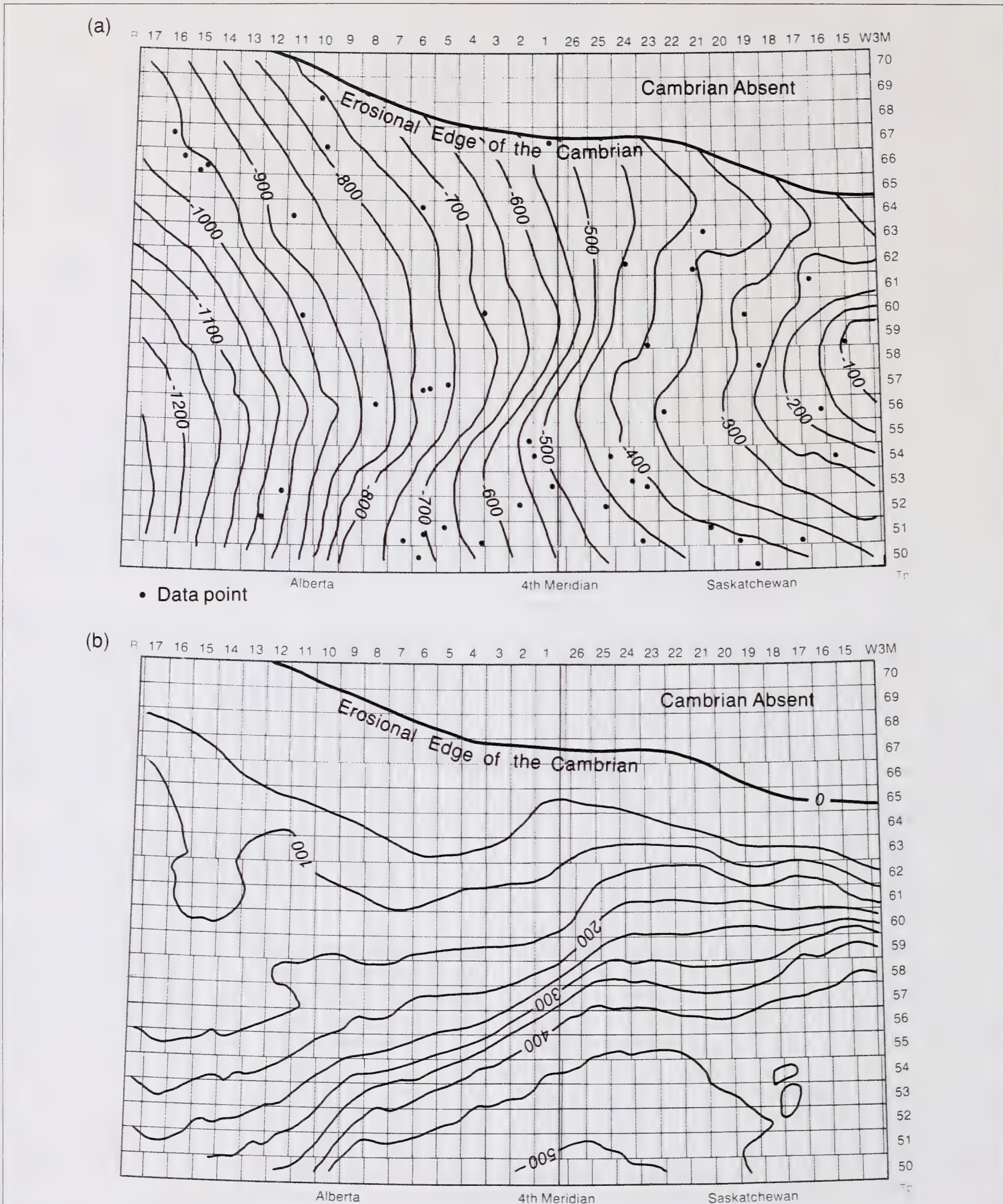


Figure 4. (a) Structure contour map on top of the Cambrian (contour interval 50 m); (b) Isopach map of the Cambrian (contour interval 50 m).

Ordovician

The Ordovician transgression extended eastward over most of the cratonic platform, depositing basal sands followed by shallow-water carbonate sediments. The shallow-water carbonate shelf environment and associated evaporitic conditions persisted well into Silurian time. An extensive pre-Devonian episode of erosion removed most of the Ordovician and Silurian strata except in the Williston Basin, which was established during the early stages of this depositional interval. Only a portion of the Red River Formation, a carbonate unit, is preserved in the southeastern corner of the study area (figure 6b). Silurian rocks are confined to the central part of the Williston Basin and are not present in the study area.

Pre-Devonian erosion was more pronounced than the pre-Middle Ordovician erosional episode, and affected parts of the Cambrian sequence not covered by Middle Ordovician strata. It left behind a northward facing, curvilinear, erosional feature known as the Meadow Lake Escarpment (figure 6a). South of the escarpment, the Cambrian was unaffected by pre-Devonian erosion, whereas to the north the Cambrian thinned markedly (figure 4b). The north side of the Meadow Lake Escarpment, a topographic low, became a depocenter for Devonian sedimentation.

Lower Devonian

The Lower Devonian comprises formations within the lower Elk Point Group (table 1). The basin configuration was controlled by the epeirogenic uplift of the cratonic arches and by the pattern of erosional relief. The lower Elk Point basin was bounded by the Tathlina Uplift, the Western Alberta and Peace River arches, and the Meadow Lake Escarpment (figure 7a). The epeiric seas transgressed from northwest to southeast. More than 400 m of Lower Devonian rocks are present in parts of the study area (figure 7b).

Initial Lower Devonian deposits consist of clastics of the Basal Red Beds, sourced from the surrounding cratonic arches. A series of massive halite units (Lower Lotsberg, Upper Lotsberg, and Cold Lake salts) onlapped the edge of the lower Elk Point basin. They reflect restricted circulation due to the presence of carbonate buildups across the northern outlet (Fuller and Porter 1969). Between the Lotsberg and Cold Lake Formations is the thin (less than 20 m) Ernestina Lake Formation, which comprises argillaceous dolomite and dolomitic shales. Figure 8 shows the distribution of the three main salt units deposited during this period in the Cold Lake region. Note that the western and southeastern margins of these salt units are depositional, while the eastern boundaries are the result of subsequent salt dissolution by meteoric water. The maximum thickness of the salt beds in the study area is about 270 m (figure 9).

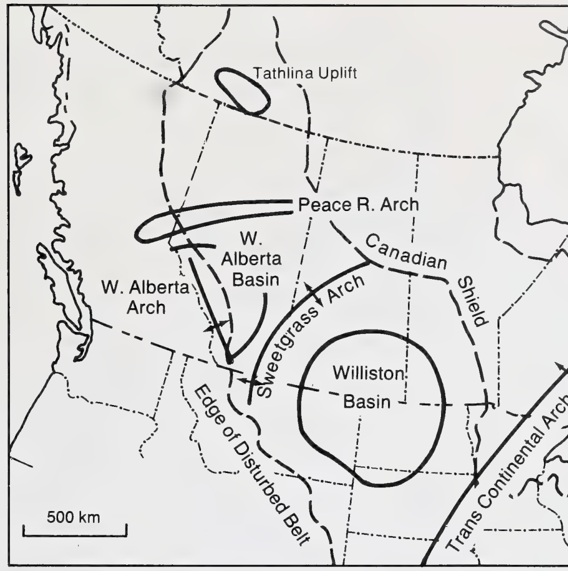


Figure 5. Cratonic arches and basins of western Canada (after Stelck 1975).

Middle Devonian

During the Middle Devonian, the sea transgressed south into the U.S.A., and the geometry of the basin changed correspondingly (figure 10a). The Peace River and Western Alberta arches remained emergent while the Meadow Lake Escarpment was completely submerged. In the Cold Lake study area, Middle Devonian rocks reach thicknesses of more than 250 m (figure 10b).

The oldest unit of the Middle Devonian comprises the argillaceous dolomite and dolomitic shales of the Contact Rapids Formation, indicating a transition from restricted to more open marine conditions.

This was followed by deposition of the widespread basal carbonate unit of the Upper Elk Point Group, which is known as the Winnipegosis Formation in the Cold Lake study area and ranges from 30-80 m in thickness. It is commonly highly dolomitized although varying thicknesses of original limestone are preserved in some areas. An isopach map of the Winnipegosis Formation shows thickening in isolated parts of the eastern portion of the study area (figure 11). These represent reefal buildups close to the eastern edge of the upper Elk Point basin.

The remaining history of the Elk Point basin was dominated by deposition of evaporites. The Prairie Formation, the most extensive evaporitic unit, developed southeast of the Presqu'ile carbonate barrier. The Peace River and Western Alberta arches remained emergent and supplied clastic sediments to the western margin of the evaporitic basin. In the Cold Lake study area, the Prairie Formation is dominantly salt, and reaches thicknesses of 160 m; along the

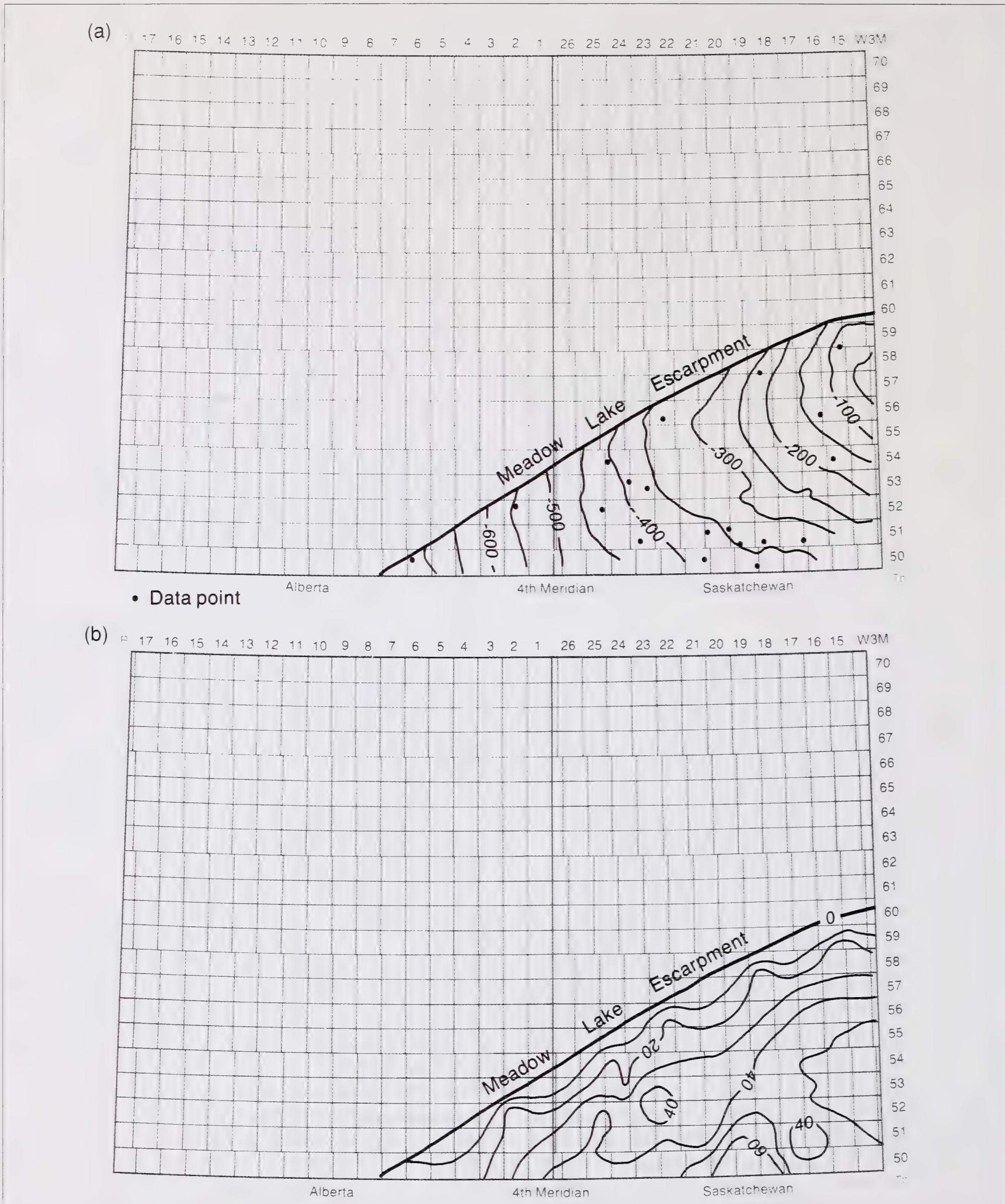


Figure 6. (a) Structure contour map on top of the Ordovician (contour interval 50 m); (b) Isopach map of the Ordovician (contour interval 10 m).

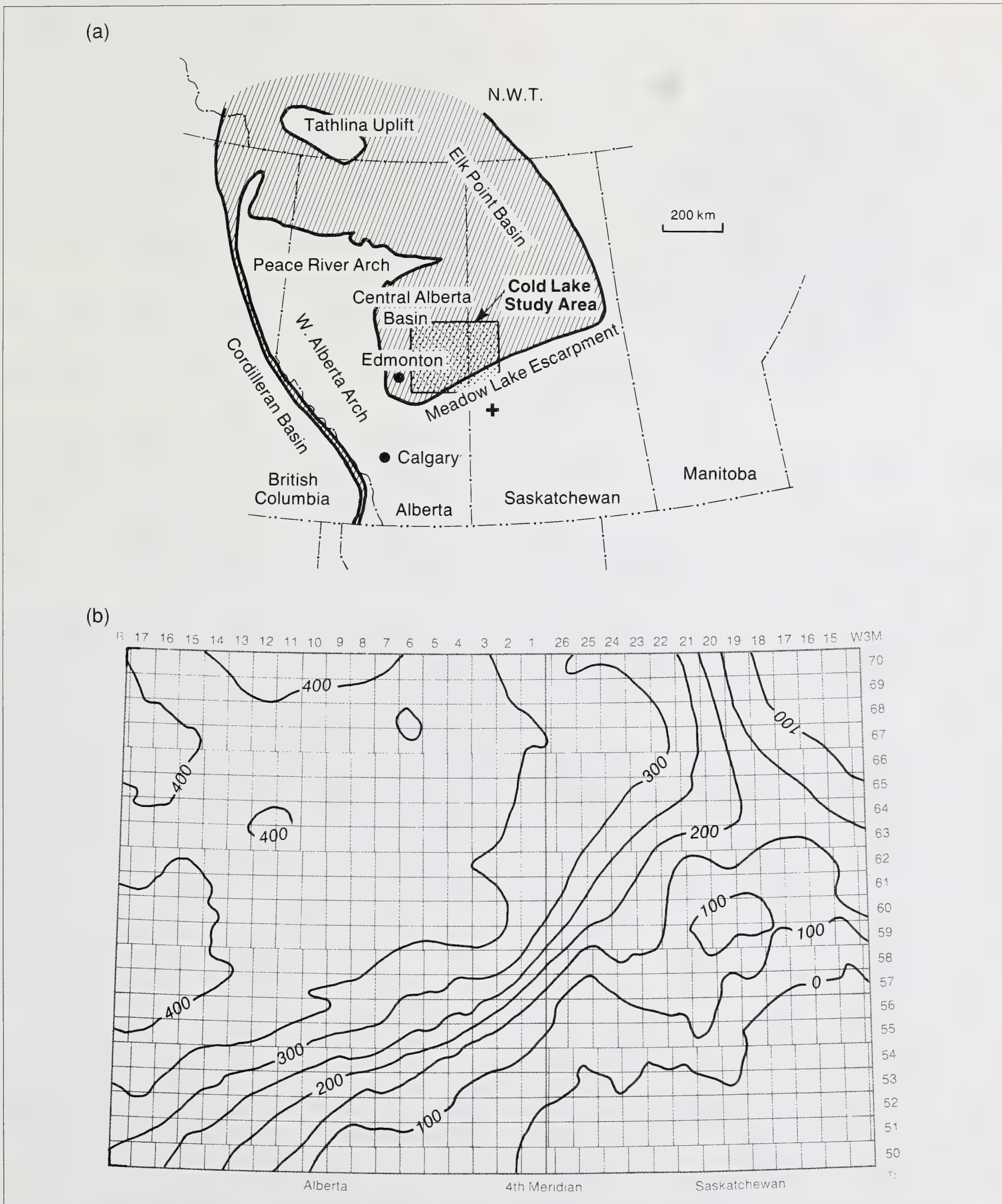


Figure 7. (a) Configuration of the Western Canada Sedimentary Basin during the Early Devonian (simplified from Grayston et al. 1964); (b) Isopach map of the Lower Devonian (contour interval 50 m).

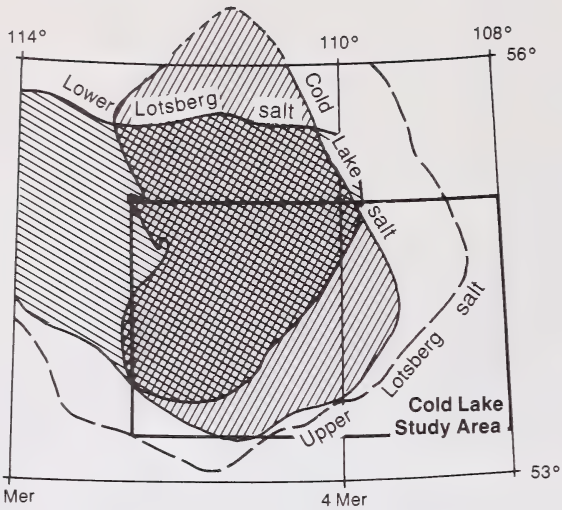


Figure 8. Distribution of Lower Devonian Elk Point Subgroup salts in the Cold Lake region (after Hamilton 1971).

eastern margin extensive salt solution has taken place (figure 12b). The effects of salt solution and the subsequent collapse of overlying strata is well illustrated by a structure contour map on top of the Prairie Formation (figure 12a). Upper Elk Point sedimentation ended with the deposition of the First Red Bed – Watt Mountain clastic interval, and a return to more widespread, normal marine conditions (Grayston et al. 1964).

Upper Devonian

The Upper Devonian depositional succession records major back-stepping and onlap of shallow marine carbonate platforms toward the interior of the continent. There was a progressive southeastward shift of platform margins and their associated reef complexes from the Slave Point edge in northwestern Alberta, to the Leduc shelf-margin complex in southern Alberta (figure 13). Widespread carbonate platforms and isolated reef complexes constitute the major components of the succession, while basin-filling limestones and shales are minor components.

In the Cold Lake study area, the Beaverhill Lake Group represents the first of these carbonate platforms and is of Middle/Upper Devonian age. Thicknesses are uniform, around 250 m, with the exception of the subcrop region where as little as 36 m remain along the eastern margin (figure 14a). A structure contour map on top of the Beaverhill Lake Group shows a uniform regional dip toward the southwest except in the subcrop region where collapse due to salt-solution in the underlying Prairie Formation has disturbed the structure. Collapse due to salt removal continued to influence the structure of formations up to Cretaceous time.

With continued transgression, the platform margin backstepped from the Swan Hills (Beaverhill Lake Group) edge in west-central Alberta to the Cooking Lake edge in central Alberta (figure 13). The platformal limestones of the Cooking Lake Formation conformably overlie the Beaverhill Lake Group and range in thickness up to 75 m in the study area. Localized reefal carbonates of the Leduc Formation occur on or near the platform margin. The combined Leduc and Cooking Lake isopach map (figure 14b) shows the position of the reefs at the southwest corner of the study area.

Shales (more correctly, argillaceous lime mudstones) of the Ireton Formation infilled the basin. With each southward transgression of the platform margin, existing reef complexes drowned, and new complexes were established on the next successive platform margin.

The succeeding Upper Devonian strata record major basin-filling and offlap of shallow-marine carbonate platforms away from the interior of the continent (figure 13). This regressive succession is characterized by argillaceous lime mudstones (generally referred to as basinal shales) capped by a thin, widespread diachronous blanket of carbonate platforms.

During the initial regression, growth of Leduc Formation reefs was terminated by the progradation of the Grosmont carbonate platform and by shales of the Ireton Formation. The Grosmont Formation is a widespread dolomitized platform carbonate, which crops out along the Peace River in northern Alberta and extends 500 km southward to its limit in the Cold Lake study area. Correlative surfaces can be traced from the platform into the basin and reflect the depositional topography at various stages during basin-filling.

In ascending order, the overlying Upper Devonian Camrose Member, and the Winterburn and Wabamun Groups formed in the same manner as the Grosmont Formation. However, due to severe pre-Cretaceous erosion, only remnants of the Grosmont and Winterburn complexes are preserved along the western margin of the Cold Lake study area. Figure 15b is an isopach map showing the total thickness of Upper Devonian strata.

A structure map of the pre-Cretaceous unconformity (figure 15a) illustrates the severity of the erosion which took place. The period from Late Fammenian (Late Devonian) to Early Neocomian (Early Cretaceous) was one of net erosion in the study area.

Evolution of the foreland basin

A major tectonic event (Columbian Orogeny) took place between the Middle Jurassic and Early Cretaceous, transforming the Western Canada Sedimentary Basin from a passive cratonic platform to an active foreland basin. Oceanic terranes and island

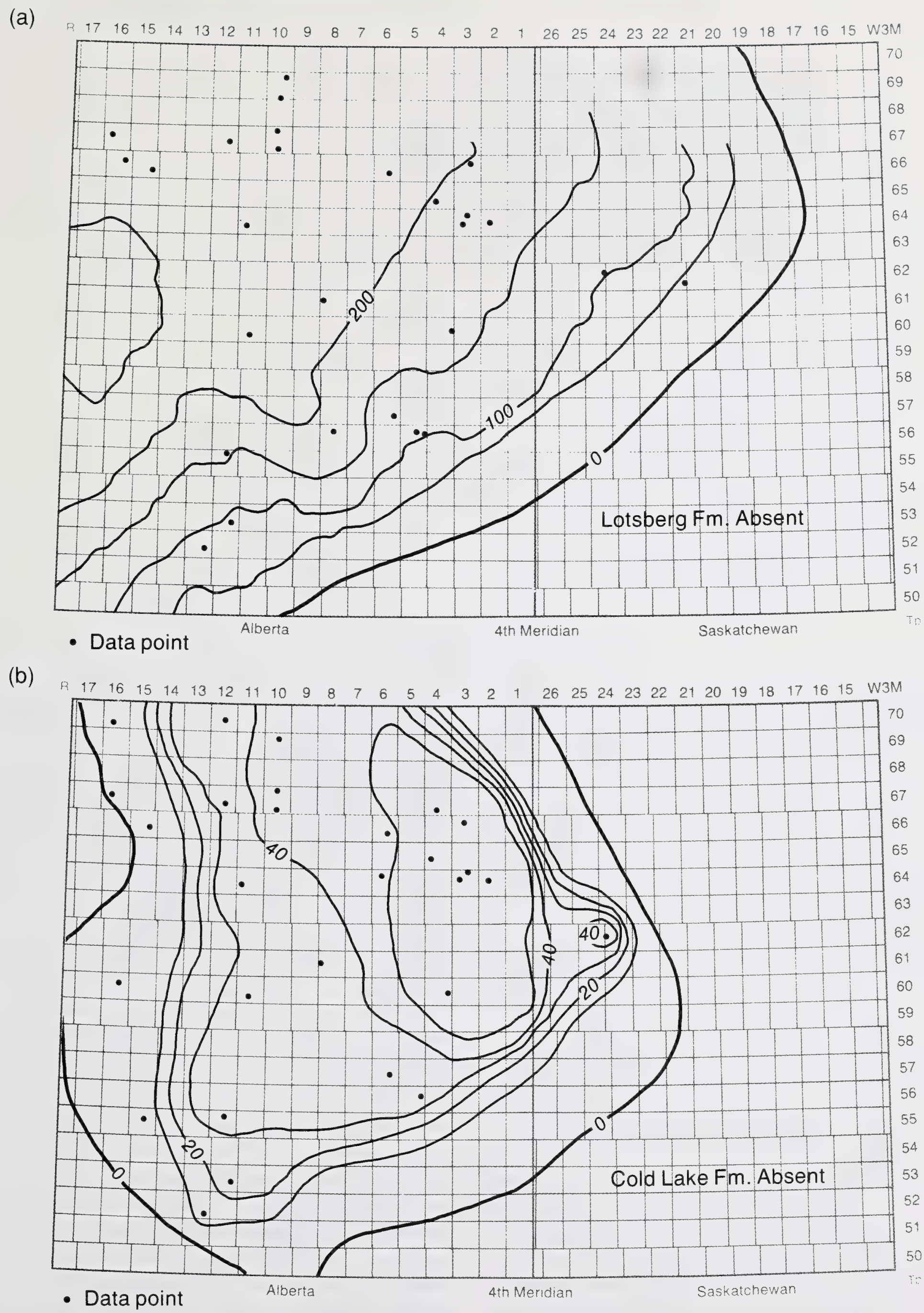


Figure 9. (a) Isopach map of the Lotsberg Formation (contour interval 50 m); (b) Isopach map of the Cold Lake Formation (contour interval 10 m).

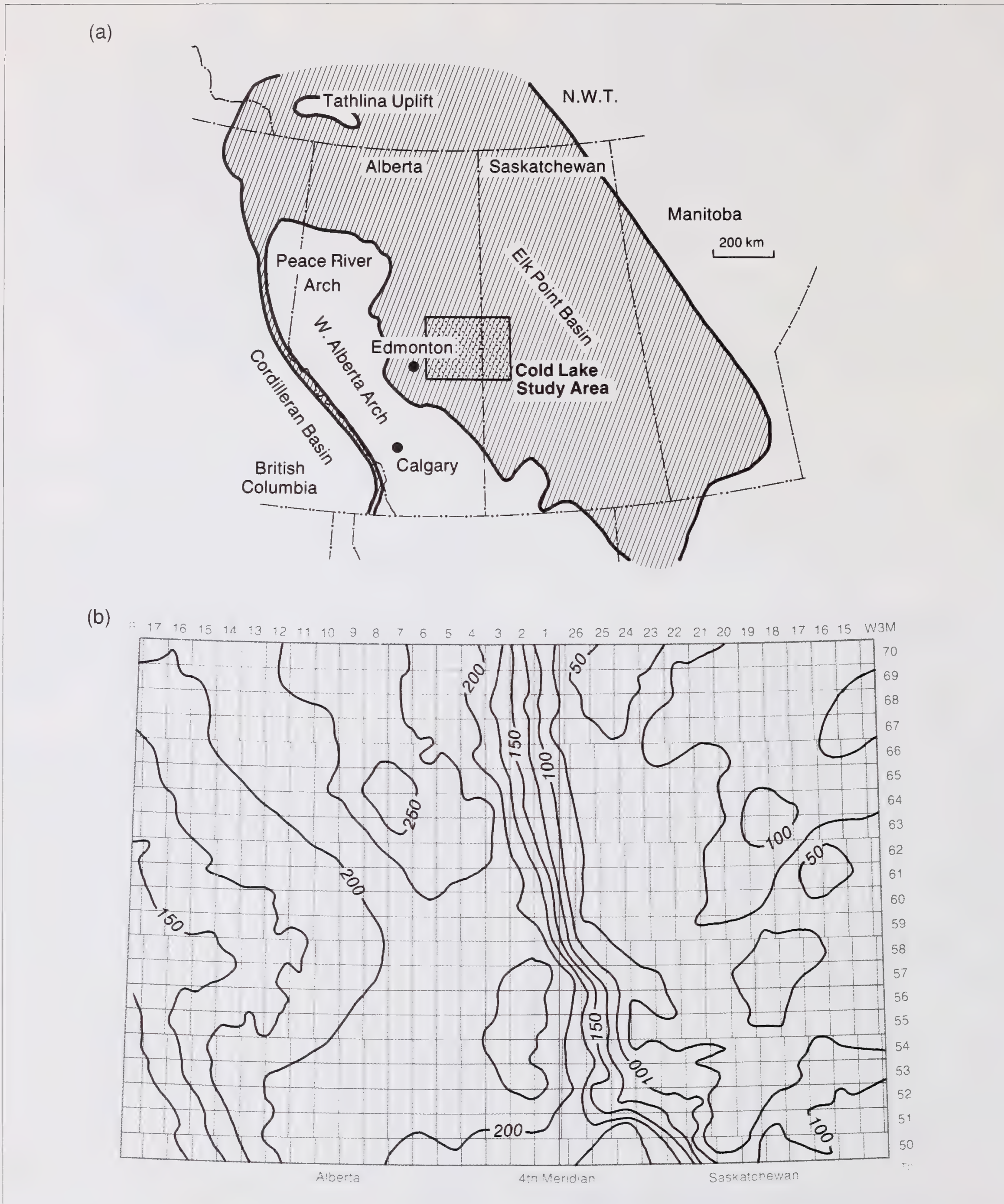


Figure 10. (a) Geometry of the Elk Point basin during Middle Devonian time (simplified from Grayston et al. 1964); (b) Isopach map of the Middle Devonian (contour interval 25 m).

Figure 11. Isopach map of the Winnipegosis Formation (contour interval 10 m).

arc complexes collided with, and accreted to, the western margin of the continent. The stable continental lithosphere responded by downward isostatic flexure to form a foreland basin, migrating ahead of the advancing mountain front (Beaumont 1981).

The shallow-water carbonates and associated evaporites which dominated the Paleozoic were superseded by stacked wedges of synorogenic clastics shed from the Cordilleran Foreland Thrust Belt. Cretaceous strata are divided into three depositional sequences corresponding to the Mannville, Colorado, and post-Colorado Groups. The Mannville represents the Columbian phase of Cordilleran deformation, the Colorado coincides with a lull in plate convergence, and the post-Colorado strata represent response to the Laramide phase of Cordilleran deformation (Beaumont 1981).

Lower Cretaceous (Mannville)

The earliest synorogenic clastic wedge shed from the emerging Cordillera consists of formations within the Mannville Group. The Mannville Group was deposited within a shallow-water basin that opened toward the northwest. The pre-Mannville unconformity surface, the basin floor, comprised westward-dipping strata ranging in age from Jurassic in the west to Devonian in the east. Differential erosion and incised drainage led to the development of a series of northwest-southeast trending ridges and valleys (figure 16). The topographic relief created by these ridges and valleys influenced sedimentation and the subsequent entrapment of heavy oil. Figure 17a shows the structure on the top of the Mannville Group and figure 17b shows the overall thickness.

The Mannville Group is divided into three subunits (Putnam 1982, Jackson 1984):

The lower Mannville was deposited as fluvial and estuarine valley-fill sediments in the incised valleys of the pre-Cretaceous unconformity surface. Lower Mannville sedimentation was activated by a marine transgression that originated from the northwest (Williams 1963). In the Cold Lake study area, these sands are known as the McMurray Formation.

The middle Mannville consists of sheet sands and shales deposited by repeated marine transgressive-regressive events (O'Connell 1985). According to Jackson (1984), middle Mannville deposition resulted from the stalling of a southward transgression of the Boreal Sea and the initiation of a major regression. The Cummings Formation represents the middle Mannville in the Cold Lake study area.

By upper Mannville time, a large influx of clastic sediments overcame basin subsidence, causing a relative lowering of sea level and the return of regressive conditions (Jackson 1984). Figure 18 shows the progradation of the shoreline from the Hoadley Barrier in central Alberta, to the Clearwater shale basin in the northwest. The upper Mannville consists of nonmarine sediments in southern Alberta, nearshore marine sediments capped by nonmarine sediments in central

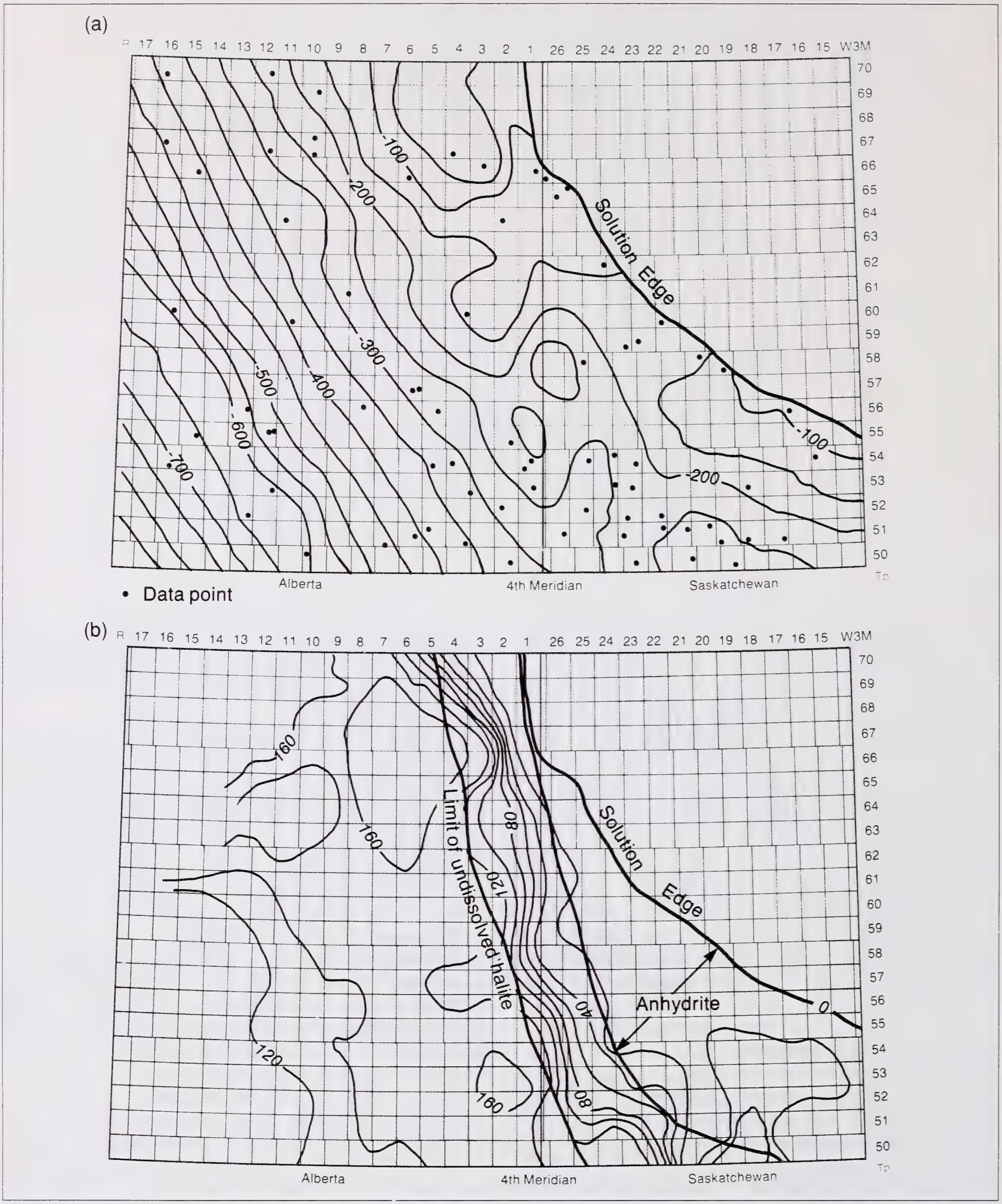


Figure 12. (a) Structure contour map on top of the Prairie Formation (contour interval 50 m); (b) Isopach map of the Prairie Formation (contour interval 20 m).

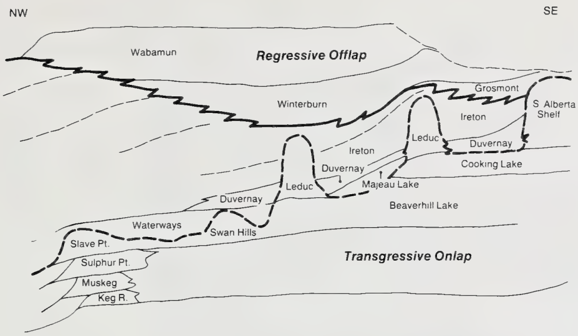


Figure 13. Schematic diagram illustrating carbonate onlap and offlap during the Upper Devonian.

Alberta (Cold Lake study area) and marine sediments in northern Alberta. In the Cold Lake study area, the Clearwater and Grand Rapids Formations make up the upper Mannville. The Clearwater Formation consists of a thick sandstone unit between thin shale layers. The shale layers represent transgressive marine pulses (figure 19). Although the shales are generally less than 10 m thick, they are the two most continuous aquitards within the Mannville Group.

In general, the Mannville Group consists of repeated alternations of marine and nonmarine deposits. Deep channels occur at all levels and are filled with either sand, or shale and silt. The complexity of Mannville sedimentation is illustrated in figure 20.

Deposition of the Mannville Group was terminated by major transgressions from the north (the Harmon shale) and from the south (the Joli Fou shale). This led to the complete inundation of the western interior, marking the beginning of the Colorado depositional sequence.

Cold Lake oil sands

The Cold Lake Oil Sand Deposit contains reserves in the McMurray, Clearwater, and Grand Rapids Formations. A schematic cross section through the northern part of the deposit is shown in figure 21. Delineation of the lateral extent and thicknesses of the individual reservoirs was obtained through several sources. Resource mapping of the Clearwater reservoir was provided by Wightman and Berezniuk (1985). The other six oil sand layers were mapped using a network of geophysical well log cross sections (unpublished) constructed by Wightman and Berezniuk (1985) and Tilley (1984). Due to the broad scale of the present study, precise mapping of the oil sand layers was not necessary. The presence of bitumen is based on above-average porosity and geophysical resistivity log readings corresponding to lower gamma ray log readings. Most of the reservoirs in the Cold Lake Oil Sand Deposit are not homogeneous or continuous (with the exception of the Clearwater reservoir), and had to be lumped together. Bitumen-saturated sands may act as aquitards and had to be delineated and incorporated into the hydrogeological system. Seven main oil sand layers are identified as a result: McMurray 1 and 2, Clearwater, Lower Grand Rapids 1 and 2, and Upper Grand Rapids 1 and 2.

The McMurray Formation is characterized by a continuous basal sand unit and an upper interbedded sand and shale unit. Minor amounts of bitumen are present in the upper thin sands, trapped against topographic highs on the pre-Cretaceous unconformity surface. The basal McMurray sands are mainly water bearing (Harrison et al. 1981).

The Clearwater, which contains highly saturated sands, is the most prolific reservoir and accounts for a significant portion of the total bitumen in place at Cold Lake (Harrison et al. 1981). The Clearwater reservoir has been the target of most pilot operations at Cold Lake because of the homogeneity and continuity of the sands.

Oil accumulation is highly variable in the Upper and Lower Grand Rapids Formation because the strata consist primarily of thin sands interbedded with shales. The trapping mechanisms in the Cold Lake region are mainly stratigraphic in nature, with some structural control over Paleozoic highs.

Upper Cretaceous (Colorado)

Deposition of the Colorado sequence was initiated by a major marine transgression which united the Boreal and Gulfian seas. By early lower Colorado time, the whole of the plains, as well as the northern foothills regions, were covered by marine waters. The dominantly argillaceous Colorado sequence was deposited during two transgressions and an intervening regression (Simpson 1975). Mud, with subordinate sand derived from the Canadian Shield, was deposited during the transgressions, and northeast-thinning sands, derived from the Cordillera, were deposited during the regression (Simpson 1975).

In the Cold Lake study area, the early transgression is represented by the dark grey shales of the Joli Fou Formation. The Spinney Hill and Viking sandstones, clastic equivalents of the first transgression and regression, are very thin (less than 4 m) in the Alberta portion of the study area and absent in the Saskatchewan part because of the offshore setting of the study area. The St. Walburg sandstone, however, attains a maximum thickness of 40 m and is the product of the last transgression; it is found only in Saskatchewan. Overall, the Colorado Group consists of 300 m of marine shales with very minor amounts of sandstone.

Upper Cretaceous (post-Colorado)

Laramide deformation and Cordilleran erosion triggered deposition of a series of eastward-thinning nonmarine, coarse clastic wedges, intercalated with muds.

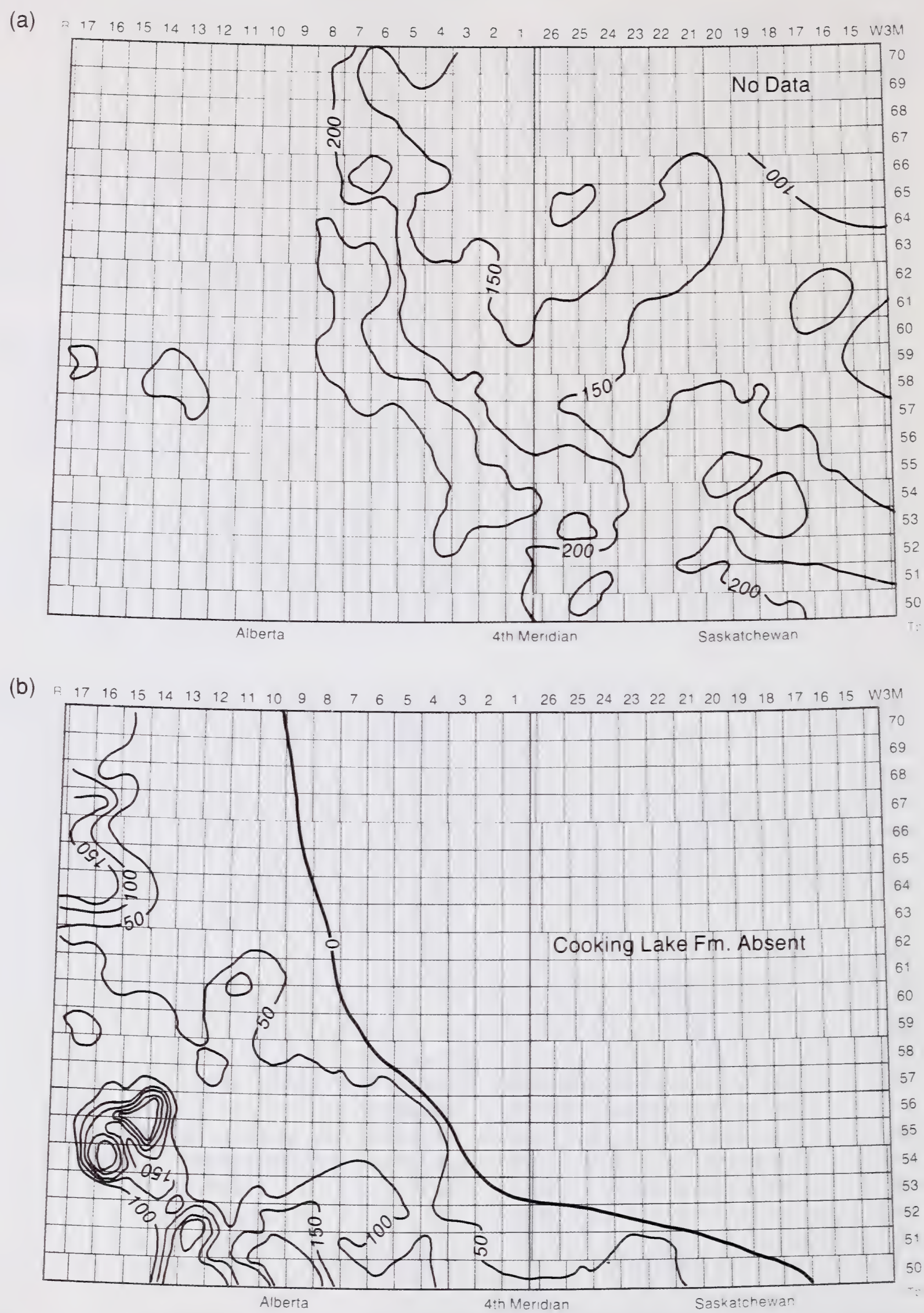


Figure 14. (a) Isopach map of the Beaverhill Lake Group (contour interval 50 m); (b) Isopach map of the Cooking Lake and Leduc Formations (contour interval 50 m).

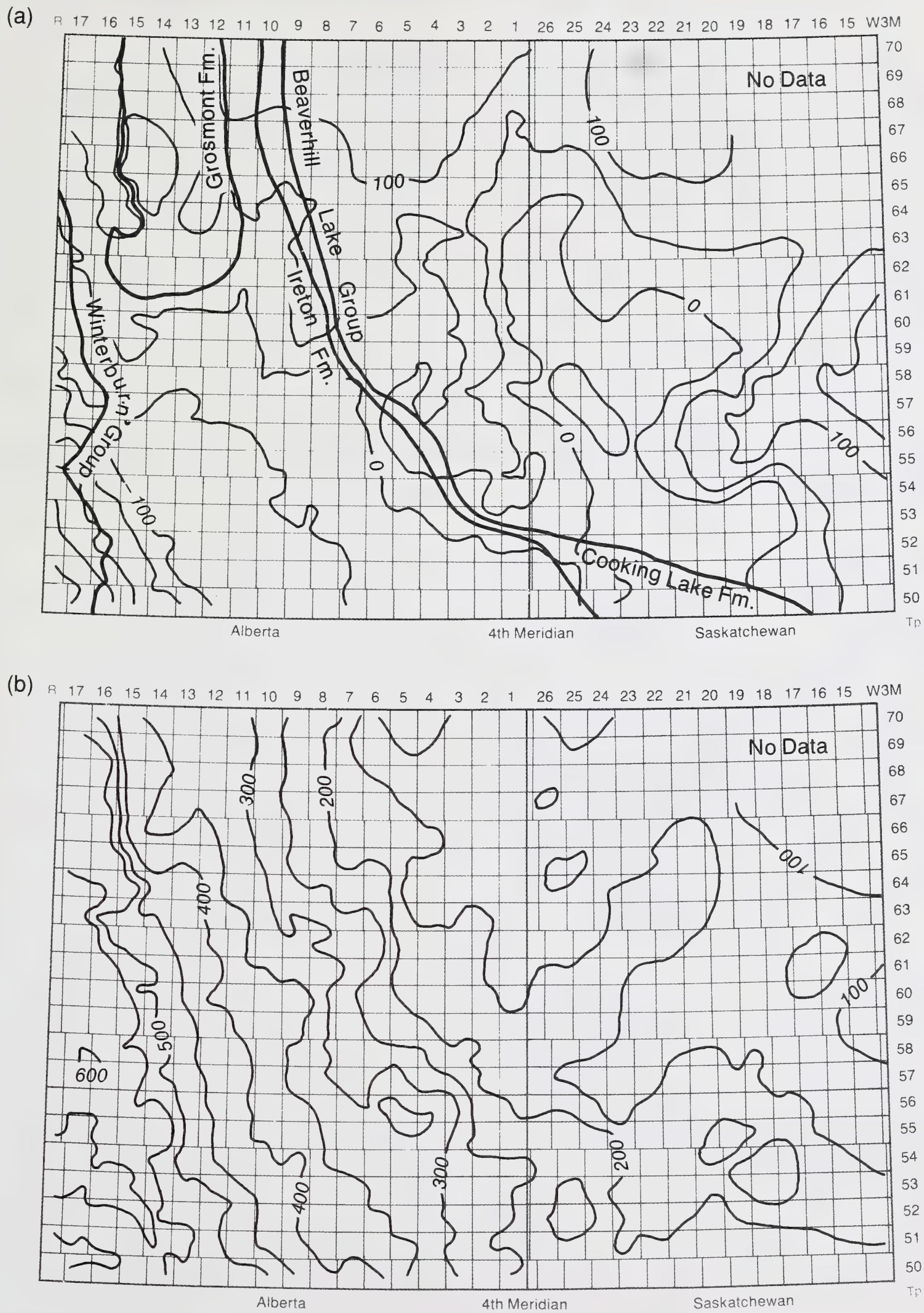
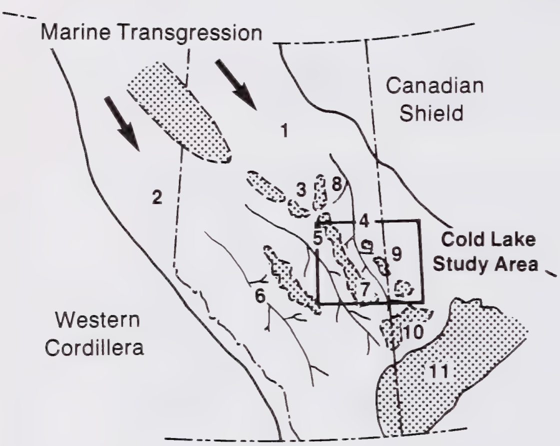


Figure 15. (a) Structure contour map on top of the pre-Cretaceous unconformity surface (contour interval 50 m, 3608 data points); (b) Isopach map of the Upper Devonian (contour interval 50 m).

The cyclicity of post-Colorado Group strata is best developed in the southern Alberta plains because of frequent marine incursions by the seaway entering the region from the south. The eastern interior plains, in which the Cold Lake study area is situated, was still a depocenter for deep water muds (Williams and Stelck 1975). These deep water muds are represented by the Lea Park and Belly River Formations. Figure 22b is an isopach map showing the thickness of the predominantly shaley succession of strata that overlies the Mannville Group.

The remainder of Phanerozoic history in the Cold Lake study area is speculative due to subsequent Tertiary and Recent erosion. It is probable that at least 1 km of strata have been removed due to this erosion (Hitchon 1984), but how much of this thickness comprised Tertiary strata is unknown. A structure contour map on the base of the Quaternary shows the paleotopography on the bedrock surface (figure 22a). Overlying the bedrock are a variety of glacial and post-glacial surficial deposits of Quaternary age.



1. Athabasca Basin
2. Gething Basin
3. Wabasca Sub-Basin
4. St. Paul Channel
5. Edmonton Channel
6. Spirit River Channel
7. Wainwright High
8. Grosmont High
9. Lindbergh High
10. North Battleford High
11. Swift Current Platform

Figure 16. Approximate Mannville paleogeography at the Aptian-Albian boundary, showing basin outlines and topographically high areas with inferred drainage (after O'Connell 1985).

Hydrogeological framework

Synthesis of the regional geology in terms of definable stratigraphic successions, together with information on the geometry of these units obtained from isopach and structure contour maps, and knowledge of their lithology, sets the scene for determination of the various hydrostratigraphic units. From this synthesis the individual aquifers, aquitards and aquicludes can be identified, not only with respect to their position within the three-dimensional framework of the study area, but also with respect to juxtaposition of similar hydrostratigraphic units. For example, in the eastern part of the study area the Lower Cretaceous Mannville Group lies unconformably on the Upper Devonian Beaverhill Lake Group, and because both are aquifers hydraulic continuity may be anticipated. The next and major part of this bulletin examines the hydrochemical, hydraulic, and geothermal properties of the hydrogeological system in the Cold Lake area to provide an analysis of the natural fluid flow and geothermal regimes.

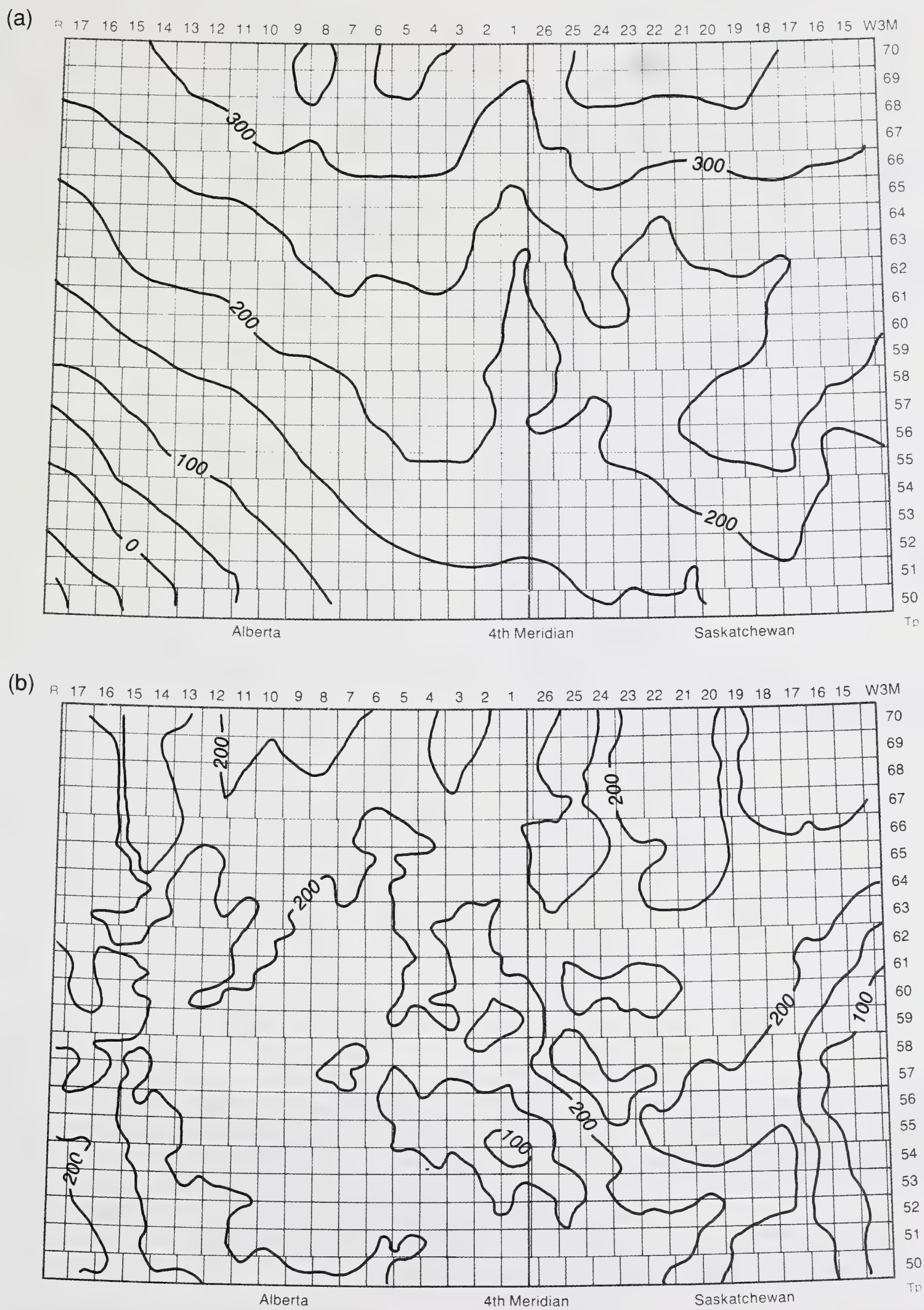


Figure 17. (a) Structure contour map on top of the Mannville Group (contour interval 50 m, 7345 data points); (b) Isopach map of the Mannville Group (contour interval 50 m).

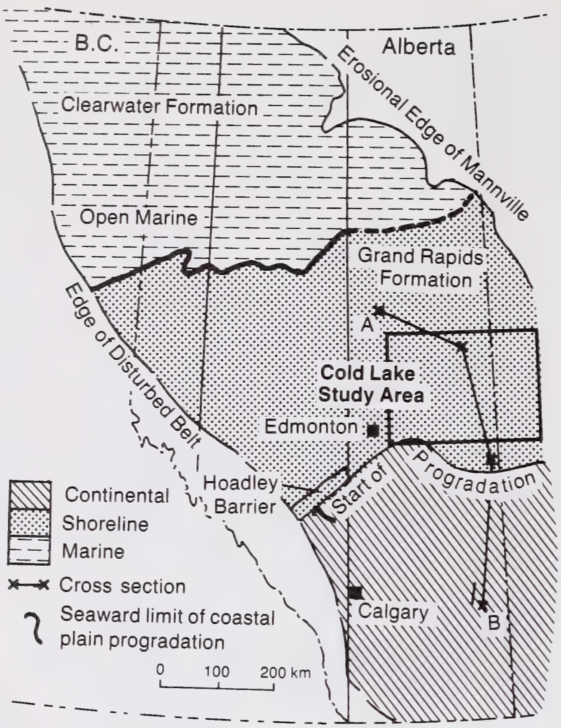


Figure 18. Progradation of the Upper Mannville shoreline from south-central Alberta northward to the Clearwater Formation marine shale basin (simplified from Jackson 1984).

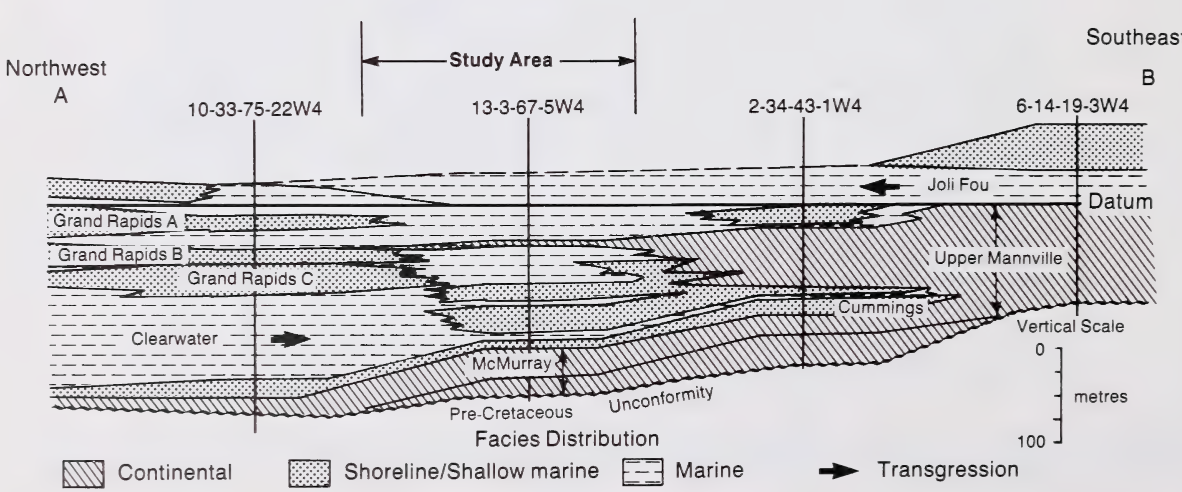


Figure 19. Schematic cross section across eastern Alberta; note the tongues of the Clearwater shale (simplified from Jackson 1984).

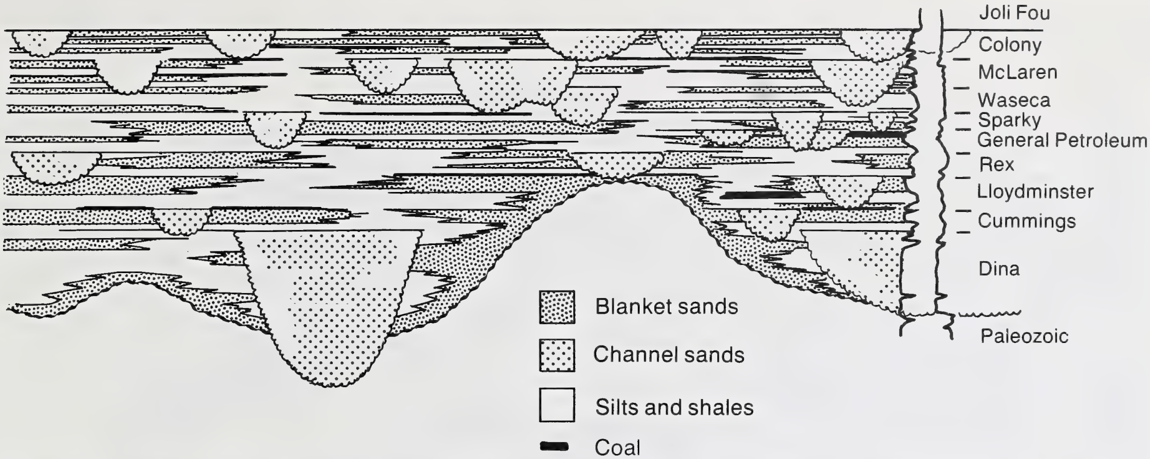


Figure 20. Conceptual diagram illustrating the occurrence and postulated relative positions of blanket and channel sands within the Mannville sequence (after Gross 1980).

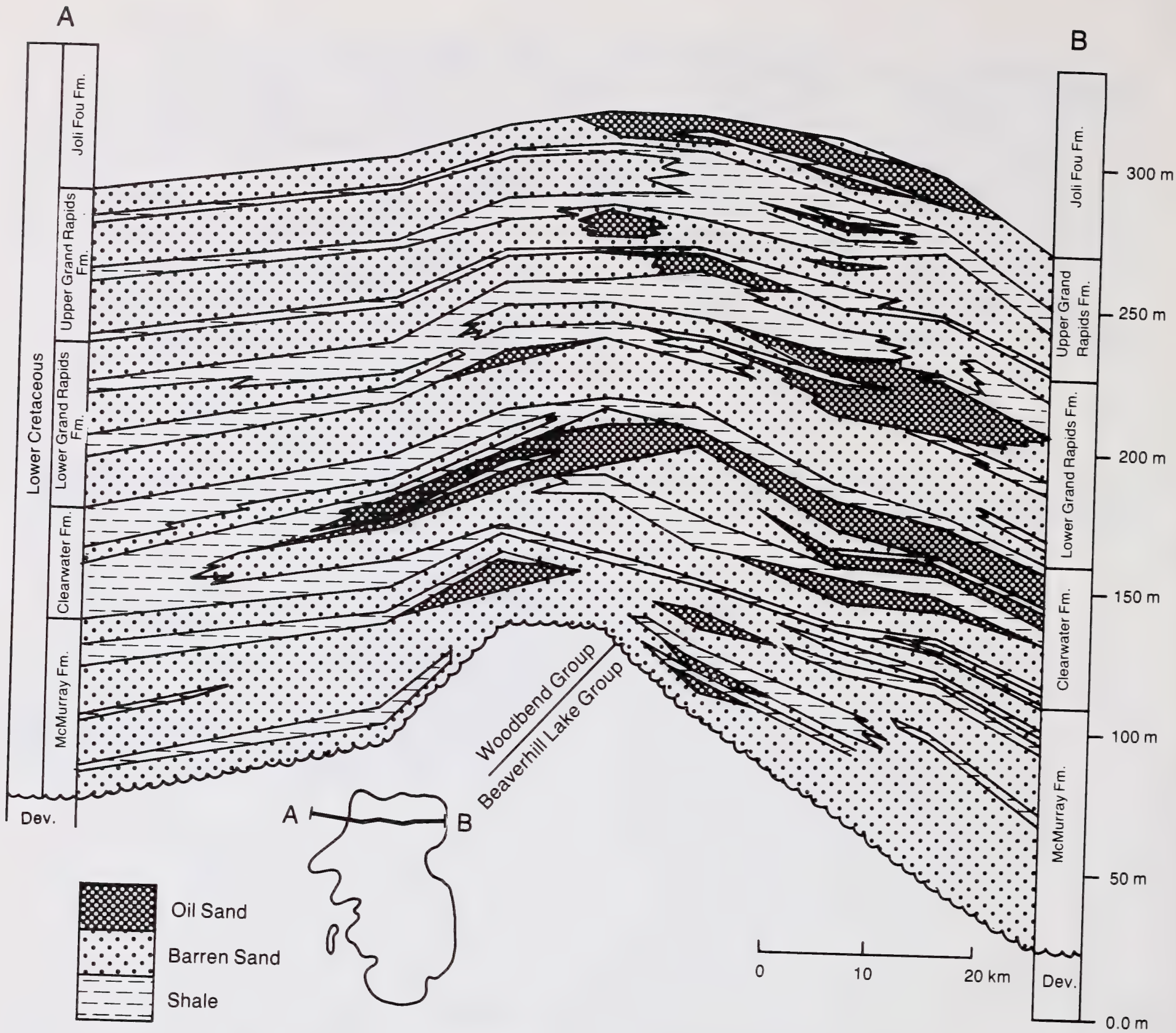


Figure 21. Cold Lake oil sands structural cross section, showing generalized lithologies and reservoir configurations (after Mossop et al. 1981).

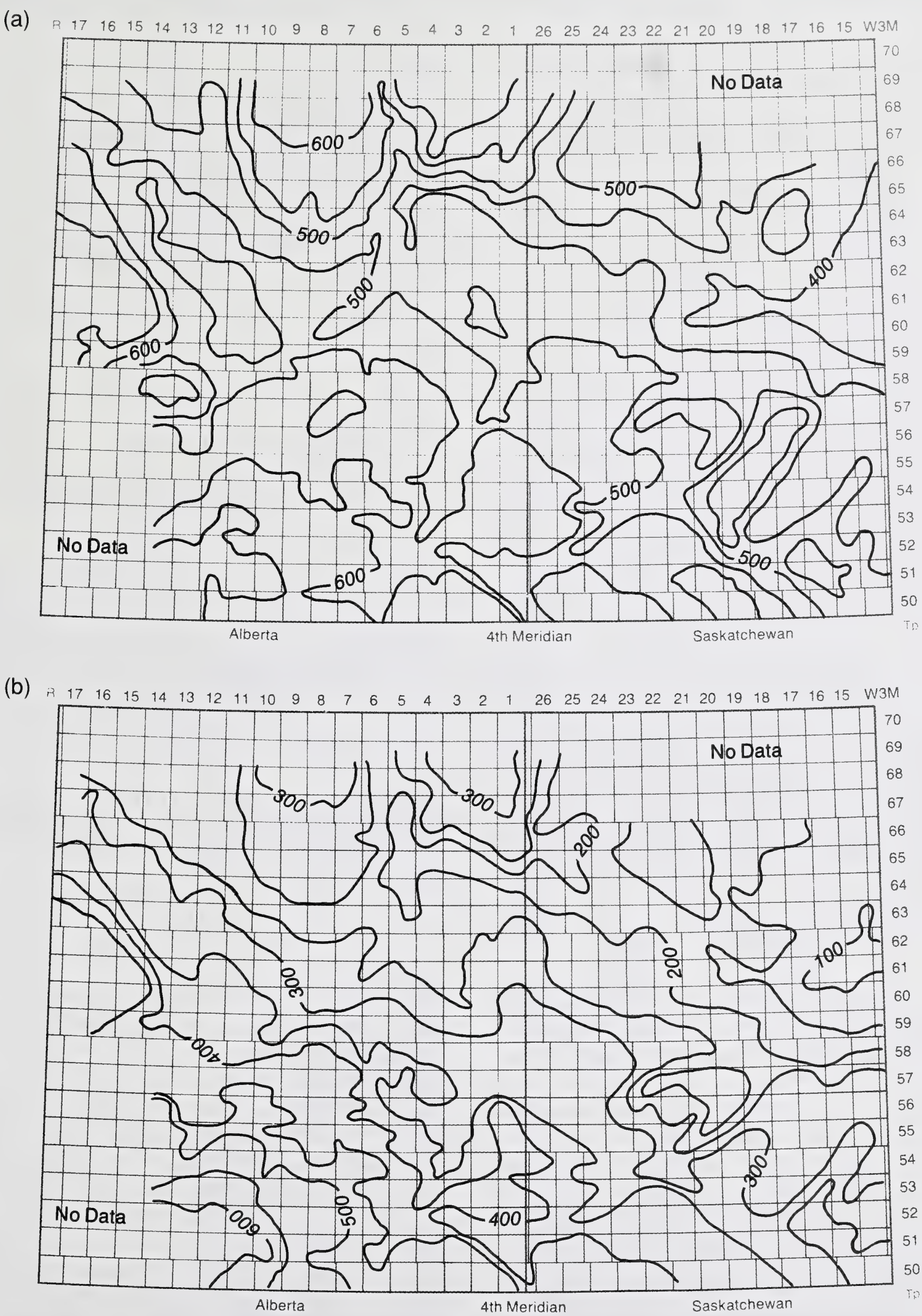


Figure 22. (a) Structure contour map at the base of the Quaternary (contour interval 50 m); (b) Isopach map from the top of the Mannville Group to the base of the Quaternary (contour interval 50 m).

Analysis of the natural fluid flow and geothermal regimes

Theoretical considerations

The word "natural" refers to the undisturbed (essentially steady-state) flow regime that has been established in the subject block of sedimentary rocks throughout geological time. Local perturbations may have been introduced into the system, especially in the study area, through the exploitation of hydrocarbon resources, but these are neglected in this regional analysis.

It is assumed that the sedimentary rocks are fully saturated with water and that the movement of this fluid is gravity-driven, although it is recognized that other driving mechanisms may exist (e.g. osmosis). Due both to the temperature increase with depth and to different concentrations of dissolved solids, the density of formation waters varies regionally within the same hydrostratigraphic unit and from unit to unit. Thus, generally, it is not possible to define a potential field driving the flow, or to show flow directions using potentiometric surfaces. The specific discharge $\bar{q}$ is given by Darcy's law, which can be expressed in the generalized form (de Marsily 1986):

$$\bar{q} = -\frac{k}{\mu}\,[\mathrm{grad}(p) + \rho g\,\mathrm{grad}(z)] \qquad (1)$$

where k is intrinsic permeability, μ is dynamic viscosity, p is pressure, ρ is density, g is the gravitational constant, and grad(z) is a vector of coordinates (0,0,1) in a system of coordinates with the vertical axis oriented upward. By defining a reference constant density, ρ_o, the above equation can also be written in the following form:

$$\bar{q} = -\frac{k\rho_o g}{\mu}\,[\mathrm{grad}(H_o) + \frac{\Delta\rho}{\rho_o}\,\mathrm{grad}(z)] \qquad (2)$$

where $\Delta\rho$ is the density variation with respect to the reference density ρ_o, and H_o is a hydraulic head defined in terms of the reference density ρ_o by:

$$H_o = \frac{p}{\rho_o g} + z \qquad (3)$$

Darcy's law as expressed by equation 2 explicitly shows that the fluid flow is driven by two forces, one external and one internal. The external force is due to piezometric head differences that normally originate from the topographic relief. The internal force is the buoyancy caused by density differences within the fluid. The advantage of this approach is that the fluid flow equation is expressed in terms of driving forces exclusive of static fluid pressure. The most common value used for the reference density is ρ_o=1000 kg/m^3 (freshwater density). However, it must be pointed out that any other constant value can be used (e.g. the minimum, the maximum or the average water density in an aquifer). The freshwater hydraulic head is defined as the water elevation in a well filled with freshwater to a level high enough to balance the existing fluid pressure at any given point. In other words, equivalent freshwater hydraulic head is a mechanism for normalizing water measurements and direct pressure measurements relative to a constant freshwater density so that they are related to fluid pressures in the aquifer in a consistent manner. Use of an equivalent freshwater hydraulic head, rather than fluid pressure, is discussed by Lusczynsky (1961), De Wiest (1965), Bear (1972), and Frind (1980).

Examination of equation 2 shows that lateral flow in a horizontal aquifer saturated with a variable density fluid can be represented by the gradients of a reference potentiometric surface H_o:

$$q_x = -\frac{k\rho_o g}{\mu}\,\frac{\partial H_o}{\partial x}; \quad q_y = -\frac{k\rho_o g}{\mu}\,\frac{\partial H_o}{\partial y} \qquad (4)$$

Vertical flow in a hydrostratigraphic unit can be due to both external forces and buoyancy, as shown by:

$$q_z = -\frac{k\rho_o g}{\mu}\,[\frac{\partial H_o}{\partial z} + \frac{\Delta\rho}{\rho_o}] \qquad (5)$$

The geometry of an aquifer can also induce a vertical component to the fluid flow. In a system of coordinates oriented downward, the vertical component of equation 1 is:

$$q_z = -\frac{k}{\mu}\,[\frac{\partial p}{\partial z} - \rho g] \qquad (6)$$

This relation allows the analysis of vertical fluid flow at any location using pressure vs depth plots. At any location there is no vertical flow at that location if the slope of the curve of pressure as a function of depth is equal to the product ρg. A slope either less than or greater than ρg shows that the flow has a downward or an upward vertical component, respectively. If the fluid density is constant, it is often convenient to represent the variation with depth of the pressure-head, $p/\rho g$, which has length dimensions. In this case, the slope of the curve $p/\rho g=f(z)$ is dimensionless and easier to compare with unity (hydrostatic). A slope less than or greater than unity shows downward or upward flow, respectively. In many cases, the pressure (or pressure-head) variation with depth is represented by a straight line, particularly when there are few data points (measurements) at the respective location.

In practice, if the fluid density is variable, the assumption commonly made is that the fluid flow is nearly horizontal and that buoyancy effects are very small and, therefore, negligible. As a result, equivalent freshwater heads effectively characterize the system. Davies (1987) has shown that it is not the absolute magnitude of the density-related error term, but rather the relative magnitude of this term vs the magnitude of the equivalent freshwater head term that determines whether density-related gravity effects will be significant in a given situation. A useful measure of the relative importance of density-related gravity effects is the dimensionless ratio of the magnitude of the equivalent freshwater head term (Davies 1987), which is a ratio defined also by Bear (1972, p. 654). Davies calls this relative strength of the two driving forces as DFR (Driving-Force Ratio), as defined by:

$$DFR = (\Delta\rho|grad(E)|)/(\rho_o|grad(H_o)|) \qquad (7)$$

where $|grad(E)|$ is the magnitude of the elevation gradient, and $|grad(H_o)|$ is the magnitude of the freshwater hydraulic gradient. Assuming an isotropic medium, Davies (1987) has shown through numerical experiments that the value DFR=0.5 is the approximate threshold at which buoyancy-related gravity effects may become significant. This threshold may vary slightly, depending on actual flow conditions and on the scale and accuracy required for a particular study. The errors introduced by the use of equivalent freshwater hydraulic heads are associated with both the magnitude and direction of the specific discharge vector.

The aquifer systems in the Phanerozoic section of the Cold Lake study area are not horizontal. The general dip is from northeast to southwest, with Paleozoic strata having more pronounced dips than do Cretaceous strata. The density of formation waters is variable, both within, as well as between hydrostratigraphic units, as will be shown subsequently. Therefore, some buoyancy-related effects must be present in the flow.

In order to assess the importance of these effects, the DFR was computed on a regional scale for selected aquifers in the study area. The DFR values for the Cretaceous Viking, Mannville, Clearwater, and McMurray aquifer systems are all less than 0.1, which is less than the threshold as defined by Davies (1987). The freshwater hydraulic head approximation is acceptable for the Beaverhill Lake aquifer system, which has a DFR value of 0.42. For the Basal Cambrian aquifer, the Driving Force Ratio has a value of 1.31 when the reference density is taken as freshwater density. However, the following considerations should be taken into account in assessing the importance of buoyancy effects in this aquifer: (1) the aquifer is practically isolated from other aquifers in the hydrostratigraphic sequence by thick, shaley and evaporitic units; (2) the density of formation waters has a minimum value of 1120 kg/m^3; and (3) the aquifer anisotropy is K_H/K_V=80. Computing the Driving Force Ratio with respect to the minimum value of formation water density in this aquifer leads to a DFR value 0.6, which shows that vertical flow due to buoyancy effects in the Basal Cambrian aquifer is negligible when the anisotropy of this aquifer is taken into account.

Based on the above theoretical and practical considerations, the lateral flow of formation waters is analysed in the following section using freshwater potentiometric surfaces which indicate the flow directions if the aquifers are assumed to be isotropic in the horizontal plane. For easier representation and analysis, the vertical flow between aquifer units is described on a local scale by pressure-head vs depth plots based on data points. On a regional scale, the analysis is performed using profiles of actual hydraulic head along cross sections. The hydraulic head profiles were produced as cross sections through surfaces of static hydraulic head computed with actual values of formation water density. Assuming that buoyancy effects are negligible, the relative position of the hydraulic head profiles of two adjacent aquifer systems separated by an aquitard shows the direction of possible vertical flow. The hydraulic head values in potentiometric surfaces and in corresponding vertical profiles do not match because of the different scaling of the pressure term, one with respect to freshwater density and one with respect to the real density of formation water. It should be pointed out here that the evaluation for possible vertical flow using pressure-head and actual hydraulic head profiles should be done only for adjacent aquifer systems with “relatively close” values of formation water density, even if more than two aquifer systems are represented in the same figure. As mentioned earlier, only in this case can the buoyancy effects be neglected for the specific conditions in the Cold Lake study area.

A hydrostratigraphic system can be regionally characterized by composite values of hydraulic parameters. The objective of the analysis of the natural fluid flow regime is to simplify the flow system into groups of units. Consequently, for a given block of sediments, one may consider two levels of definition for the hydrostratigraphy: an initial level based on the geometry and lithology of the individual stratigraphic units, and a second (synthesis) level based on the regional analysis of the fluid flow.

Information on the geothermal regime in the subsurface environment is important in hydrogeological studies for several reasons. The flow of fluids and heat are coupled phenomena, influencing each other in different ways; for example, the convective transport of heat can become important in the case of strong fluid flow driven by hydraulic head differences. On the other hand, natural convection of fluids can occur as a result of significant temperature differences. The ther-

mal field also plays a significant role in water-rock processes, because many reactions are temperature dependent. Knowledge of the geothermal field is important when the variations in fluid density due to temperature changes are no longer negligible.

There is a basic difference between the flow of fluids and the flow of heat in the subsurface environment. While the fluid can flow and thereby transport formation waters only through the porous and/or fractured space, the heat flows through both the solid and fluid phases of the porous medium.

As pointed out by Bachu (1988), in the case of complex hydrostratigraphic basins it is difficult to assess the importance of convective vs conductive heat flow using numerical modelling, or using detailed quantitative descriptions of each parameter and variable involved. The problem is compounded in cases like the Cold Lake study area, where the amount of the available data and information requires automatic processing. In such cases, dimensional analysis provides a tool for assessing the effects of fluid flow on the geothermal regime.

In the case of gravity-driven fluid flow in sedimentary basins, a measure of the intensity of convective heat transfer vs conductive heat transfer is given by the Peclet number. The Peclet number is not characterized by the existence of a critical value below which the system is conductive, as in the case of the critical Rayleigh number in natural convection. However, for Peclet numbers much less than unity, the system is conduction dominated, while for values significantly greater than unity the system is convection dominated. An order of magnitude of one for the Peclet number indicates a conductive-convective system.

Bachu (1985) determined the Peclet number for various strata in the Cold Lake region based on about 1700 temperature measurements from oil fields and drillstem tests. More recently, the Peclet numbers were recalculated using 19 218 bottomhole temperature values in the Cold Lake study area (Basin Analysis Group 1988). The values of Peclet number for the hydrostratigraphic units in the Cold Lake study area vary between 10^{-5} (Clearwater shale) and 10^{-2} (Basal Cambrian sandstone), with values mostly around 10^{-3}. It follows that the convective heat transfer in the sedimentary rocks is negligible throughout the Cold Lake study area and that the main mechanism for heat transport from the basement to the ground surface is thermal conduction through the sedimentary column. Therefore, in the absence of tectonic processes, the heat flux crossing the sedimentary basin produces a vertical temperature distribution and a geothermal gradient depending ultimately on the geometry and lithology of the strata (Bachu 1985).

In this section of the bulletin, the fluid flow and geothermal regimes are analysed from the base upward and integrated as much as possible. Because of the commonly observed relations between the fluid flow and the hydrochemical regimes (parallel trends of hydraulic gradient and salinity gradient), the hydrochemistry is integrated in this analysis. Regional hydrochemical variations are illustrated, wherever possible, by maps of salinity (calculated total dissolved solids). Additional data on the regional values of hydraulic parameters and variables are presented for each hydrostratigraphic unit in the Appendix. This analysis of the natural fluid flow regime is based on selected information for 1858 analyses of formation waters, 2155 drillstem tests and 46 700 core analyses. Because of the uneven distribution of these data in three dimensions, all of the information related to the Paleozoic strata has been examined and used whenever possible; preselections have been made for drillstem test results for the Cretaceous aquifers. Given the paucity of hydrochemical and hydrodynamic data, the hydrogeology of the Lower Paleozoic rocks is not clearly understood in the study area. The distribution of bottomhole temperatures is also very uneven, with most of the data in the Mannville Group (5363), and at the top of the Paleozoic (4446), the explanation probably being that the drilling was stopped once past the Cretaceous oil sands and heavy oil deposits. However, 47 wells record bottomhole temperatures at the top of the Precambrian, and there are some temperature measurements between the Precambrian and the Beaverhill Lake Group, to allow characterization of the thermal regime in this succession.

Typically, for each identified hydrostratigraphic unit, the following items will be examined successively: (1) the geometry of the unit; (2) the hydrochemistry; (3) the hydrogeology (fluid flow conditions and hydraulic parameters); and (4) the geothermal regime.

Lateral flow regimes

Precambrian aquiclude

For the purpose of this study, and as a general observation, the Precambrian basement is assumed to be an aquiclude and, therefore, its top is a no-flow boundary. Although recent studies (e.g. Fritz and Frape 1987) have demonstrated the presence of saline formation waters (some exceeding 200 000 mg/L at depths greater than 1 km in the exposed Canadian Shield), no work has been done in western Canada which would indicate similar saline formation waters, even at shallower depths, in the covered Precambrian.

Measured temperatures at 47 locations at the top of the Precambrian (base of the Basal Cambrian sandstone) vary between 24°C at a depth of 746 m in the northeast of the study area, and 70°C at a depth of 1997 m in the southwest. The temperatures generally decrease in an updip direction (figure 23). However, a few features alter this general pattern. In the southeast corner there is an increase in temperatures,

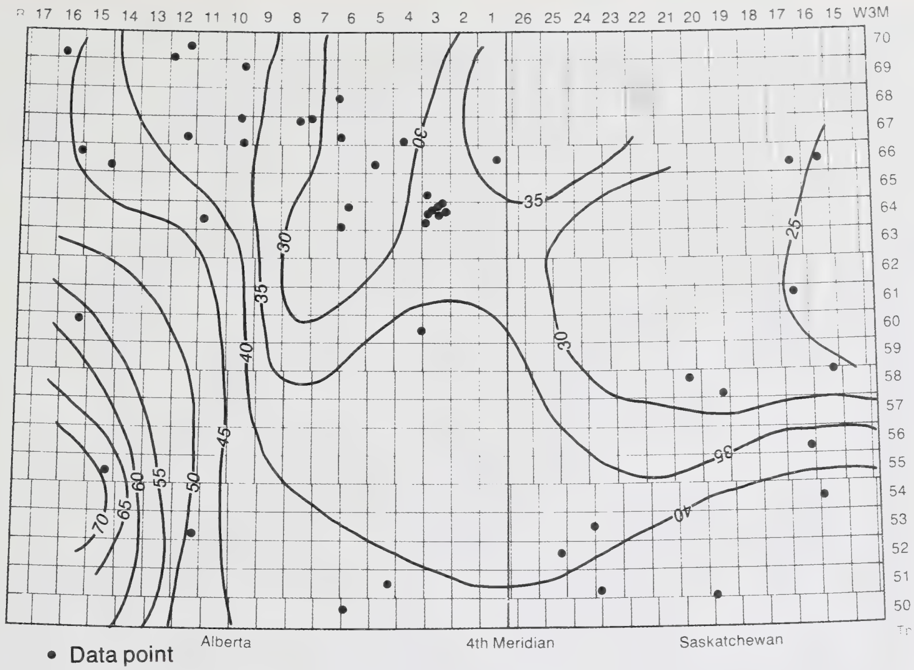


Figure 23. Temperature distribution at the top of the Precambrian (base of Basal Cambrian sandstone); 5°C isotherms.

as well as in the north-northeast part of the study area. In the western third of the study area the isotherms are crowded, while in the rest, particularly in the center, they are widely spaced. These features in the temperature distribution at the top of the Precambrian can be linked with changes in stratigraphy and lithology, as will be shown later.

Basal Cambrian aquifer

The subcrop edge of the Basal Cambrian sandstone is close to the northern boundary of the study area throughout most of the region (figure 24b). The aquifer ranges in thickness to more than 150 m in the southeast corner, and to generally 75-100 m along the southern boundary (figure 3b).

Only six reliable analyses of formation waters are available from this aquifer (table 2). The dominant ions are Na and Cl, and the formation waters are characteristically very saline (calculated total dissolved solids 238 000 to 310 000 mg/L) with relatively low contents of Ca (1250 to 3400 mg/L) and Mg (390 to 870 mg/L), and high contents of SO_4 (1570 to 6500 mg/L). In one sample, Br and I are reported at 44 mg/L and 6 mg/L, respectively. These features suggest a source of the solutes from evaporites, dominantly halite, and all six analyses are found in the region of preserved Middle Devonian Prairie Formation halite.

Lateral flow is in two main directions (figure 24b): from the southwest to northeast in the southern part of the study area, and generally from west-southwest to east-northeast in the western part. Because only six reliable drillstem tests are available close to the northern edge, the potentiometric surface of figure 24b was produced from a more regional trend that includes a well in the Lloydminster area (B12-30-49-27-W3M) and other information south and west of the Cold Lake study area. This was automatically produced by 'cutting' the electronic (computer based) potentiometric surface for the Basal Cambrian aquifer in south-central Alberta (Bachu et al. 1986) and transferring it to the Cold Lake study area with the proper coordinate transform and change of scale. The absence of the aquifer in the north-northeastern part of the area explains why the majority of the lateral flow in this aquifer is to the east after the merging of the two previously described components. This is in agreement with the decrease of the salinity gradients (figure 24a).

Based on the values determined from the six drillstem tests and from the core data (available at five different locations in the north-central part of the study area), the hydraulic conductivity is typically between 0.002 and 0.2 m/d and the specific storage between 1×10^{-5} m^{-1} and 5×10^{-4} m^{-1}.

There are only 10 bottomhole temperature measurements in the Basal Cambrian sandstone, mainly in the north, and another 10 measurements in the rest of the thick Cambrian section, mainly in the Saskatchewan portion of the study area. Values range

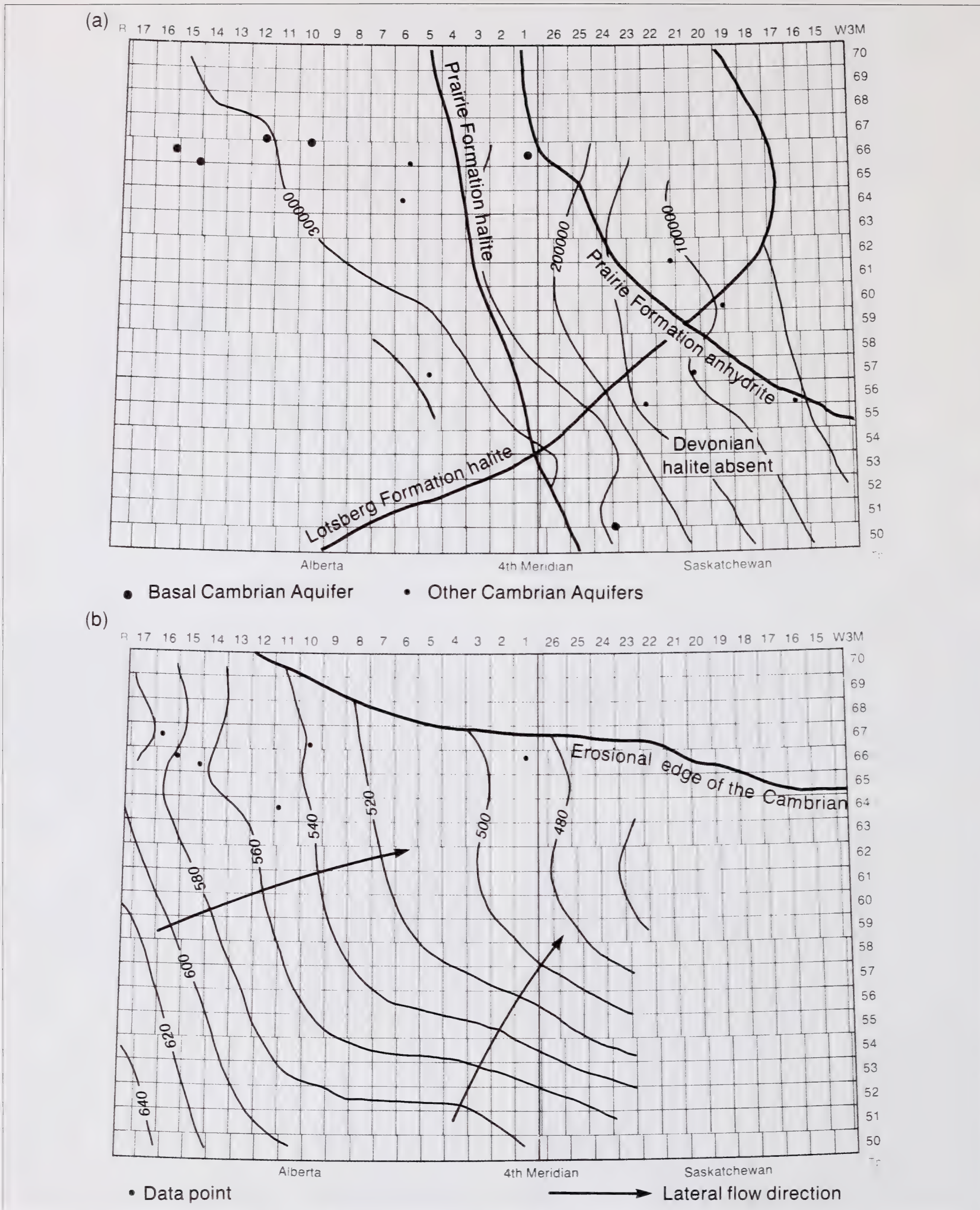


Figure 24. Cambrian hydrogeology. (a) Salinity (mg/L) of formation waters; (b) Potentiometric surface of the Basal Cambrian aquifer.

Table 2. Chemical composition (mg/L), physical properties and production data for formation waters from the Basal Cambrian aquifer.

Location	10-7-51-24-W3M	7-22-66-1-W4M	10-12-66-15-W4M	6-25-66-16-W4M	11-3-67-10-W4M	10-11-67-12-W4M*
Depth (m)	1506.6-1537.1	1133.6-1164.0	1531.6-1562.1	1563.6-1606.9	1449.3-1480.7	1446.0-1482.2
Source	DST 1	DST 5	DST 6	DST 5	DST 3	DST 3
Recovery	1274.1 m sw	868.7 m sw	1090 m sw 213.4 m mud	1310.6 m sw	652.3 m sw	1073.5 m sw 54.9 m mud
Na (diff.)	90 670	89 939	116 695	117 309	107 184	116 663
Ca	2 127	2 158	1 247	3 416	1 696	1 759
Mg	867	508	630	389	566	751
Cl	143 704	139 000	180 800	186 843	167 125	182 965
HCO_3	220	290	320	120	102	30
SO_4	3 080	6 526	4 066	1 565	3 718	3 000
TDS (110°C)	–	240 001	306 920	322 920	–	316 060
TDS (ignition)	–	232 730	301 020	302 160	–	307 150
TDS (calc.)	240 557	238 274	303 595	309 581	280 338	305 153
pH (laboratory)	6.4	7.6	7.1	7.8	6.4	5.91
Density (15.56°C)	1.1642	1.154	1.195	1.199	1.1622	1.2032
Refractive Index	–	1.3818 (25°C)	–	1.377 (22.8°C)	–	
Resistivity (ohm m)	0.045 (22.8°C)	0.053 (20°C)	0.055 (20°C)	0.047 (20°C)	0.044 (22.8°C)	0.0312 (25°C)

– = not determined; * Br = 44 mg/L; I = 6 mg/L; sw = salt water

between 21°C and 47°C at depths between 867 m and 1501 m. Because these data are scattered over the entire thickness of the Cambrian, two-dimensional representation of the three-dimensional distribution was considered meaningless.

Other Cambrian aquifers

The subcrop margin of Middle and Upper Cambrian strata younger than the basal sandstone is a sinuous boundary lying about five townships south of the northern edge of the study area (figure 24b). These strata are less than 100 m thick to the northwest of the Meadow Lake Escarpment, but the preserved thickness increases to 100 to 250 m along the escarpment edge. Beneath overlying Ordovician rocks the thickness of the post-basal sandstone Cambrian sequence is in the range of 350 to more than 400 m.

Nine reliable formation water analyses are available from these aquifers. Although salinities are lower (60 000 to 130 000 mg/L) in the eastern part of the study area, where depths are generally less than 1 km, all nine analyses are dominantly NaCl solutions with similar ranges to those in the Basal Cambrian aquifer for Ca (1190 to 4760 mg/L), Mg (315 to 2400 mg/L), and SO_4 (1300 to 6260 mg/L). The lower salinities in the eastern part of the study area are related more to the absence of halite beds in the overlying Lower and Middle Devonian than to the shallower depths (figure 24a). These facts suggest that all 15 formation water analyses from Cambrian aquifers should be treated as a single population and the salinity map (figure 24a) therefore includes all data from these rocks. Regional trends of Na, Cl, and density, and to a lesser degree Ca and Mg, are generally parallel to those for salinity, but the isoconcentration contours for SO_4 and HCO_3 tend to have a more east-west component, and the concentration gradient of these ions is opposite to that of salinity; the cause of this difference is explained in the section dealing with the Winnipegosis aquifer system.

Middle and Upper Cambrian strata are generally composed of thin intercalations of sandstone and shale. A value of 0.01 m/d, similar to the values obtained for the Basal Cambrian aquifer, was found for the only reliable drillstem test available; at two locations in the north-central part of the study area (Tp 64 and 65 R 3 W4M) the average maximum horizontal conductivity is five times greater than that determined at the same location in the Basal Cambrian aquifer. Thus, in spite of the presence of thin beds of shale and siltstone in the Middle and Upper Cambrian, the Cambrian rocks dominantly play the role of a single aquifer system, albeit with contrasting permeabilities within it.

Ordovician aquifer

A thin (less than 60 m) sequence of Ordovician rocks caps the Meadow Lake Escarpment, preserved beneath Devonian strata (figure 6b). No reliable formation waters have been recovered from this aquifer in the study area, mainly due to poor recovery or sampling position. However, what data are available suggest that formation waters from Ordovician rocks are similar to those in the underlying Cambrian.

No information from drillstem tests or cores is available for the Ordovician aquifer within the study area and, wherever present, this aquifer is amalgamated with the Cambrian aquifer system described above.

Basal Red Beds "aquifer"
These Lower Devonian rocks of evaporitic clastic origin have the typical hydraulic conductivity ($7.5x10^{-8}$ m/d) of an aquitard at 7-22-66-1 W4M, but at 4-5-66-16 W4M, the drillstem test hydraulic conductivity is 0.62 m/d. This observation is confirmed by the core data; at two locations in 64-3 W4M, the horizontal component of hydraulic conductivity has values between $5x10^{-5}$ and $8x10^{-2}$ m/d in cores which were recovered from about 80 percent of the total formation thickness. Although the range is large, the representative average is 0.01 m/d. Cores from the lower half of this unit at 57-6 W4M and 66-6 W4M have an overall range of $2.1x10^{-4}$ to 0.41 m/d for the horizontal conductivity. Although these values are confined to a narrow north-south band in the center of the study area, this information shows that the behavior of the Basal Red Beds is more typical of an aquifer than of an aquitard.

Lower Paleozoic aquifer system
The plot of figure 25a illustrates the similarity of hydraulic behavior at a variety of locations for the three above-described units: all point data fall within a narrow (50 m) range of pressure-head for a given depth, which is an acceptable variation considering the wide areal distribution of the data. The plot in figure 25b, although corresponding to a well located just outside the study area, shows that there is an overall differential in hydraulic head between the Winnipegosis and Basal Cambrian aquifers in the area where Lower and Middle Devonian halite beds are absent. It is a matter of interpretation whether the head differential occurs gradually over the Cambrian or occurs as a sharp break at some level within it. Because data simply are not available to support either interpretation, and for the purpose of the study, the entire Cambrian, Ordovician, and Lower Devonian Basal Red Beds are combined into the Lower Paleozoic aquifer system with hydraulic continuity and contrasting hydraulic conductivities between the four subunits.

The Lower Paleozoic aquifer system ranges in thickness up to 562 m (figure 26). Over most of the study area it is confined between the underlying Precambrian aquiclude and the overlying Lower Devonian aquiclude; along parts of the eastern and southeastern margins of the study area, however, this unit is in direct contact with the Winnipegosis aquifer system (see figure 28b).

Lower Devonian aquiclude system
Lower Devonian rocks of the Lower Elk Point Group (Grayston et al. 1964) overlie Lower Paleozoic strata north of the Meadow Lake Escarpment. They comprise, in ascending order, evaporitic clastics (Basal Red Beds, included within the Lower Paleozoic aquifer system) and massive halite beds (Lotsberg and Cold Lake Formations) with an intervening argillaceous

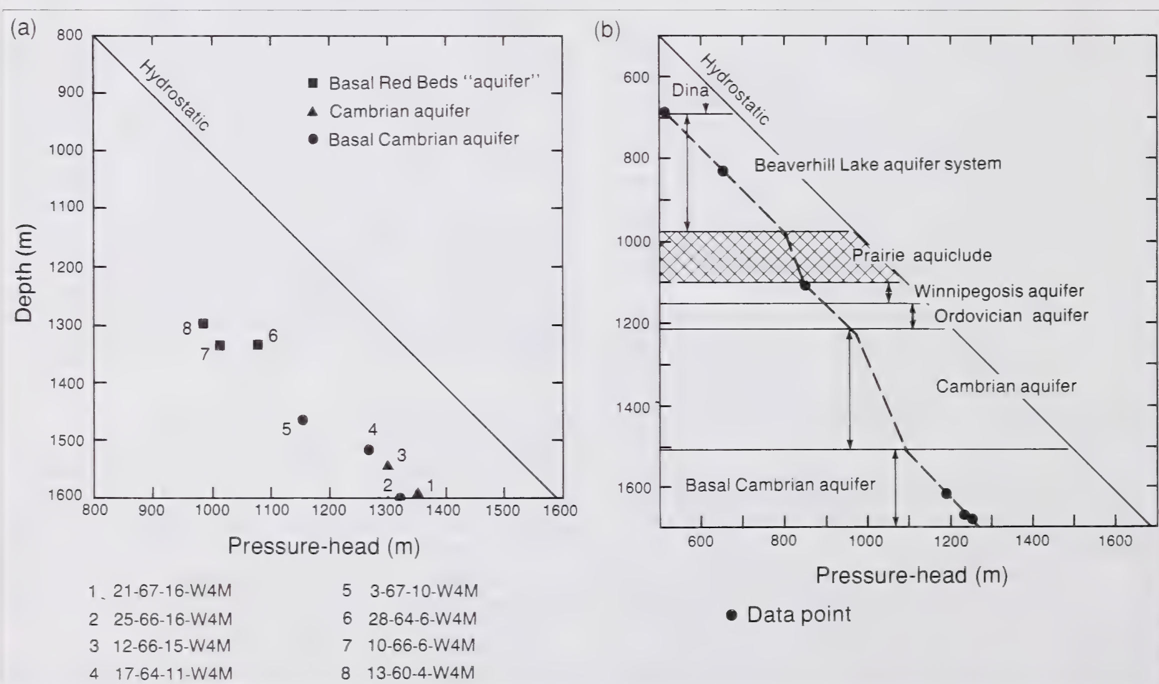


Figure 25. Cross-formational flow as illustrated by pressure-head vs depth plots in the Lower Paleozoic aquifer system. (a) At the indicated well locations; (b) Just south of the study area at 12-30-49-27-W3M.

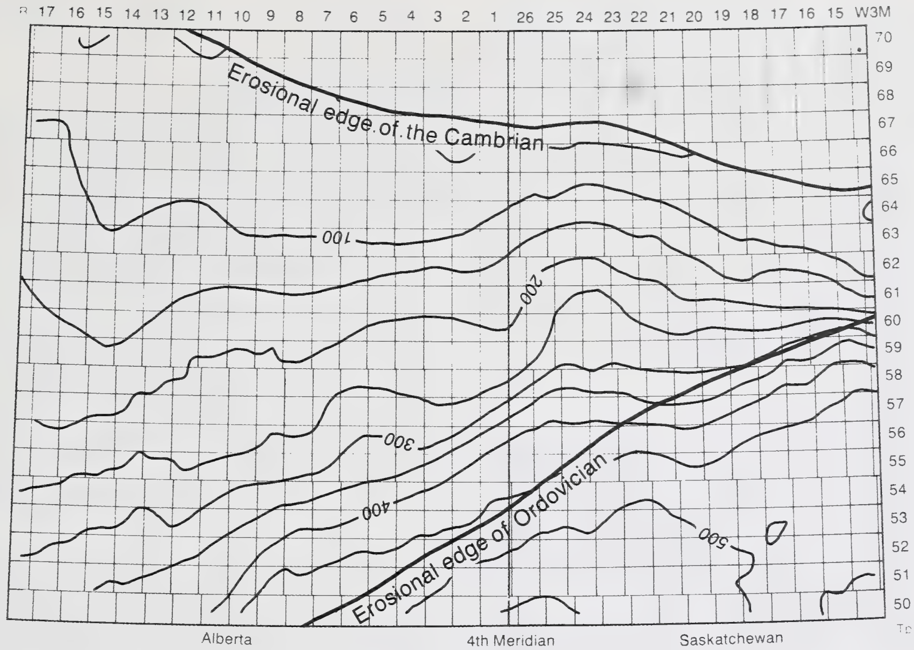


Figure 26. Isopachs of the Lower Paleozoic aquifer system (contour interval 50 m).

dolomite and dolomitic shale unit (Ernestina Lake Formation). Although formation waters have been recovered from a few thin, more porous and permeable beds, none of the analyses is reliable, for a variety of reasons. Because halite beds dominate, and porous and permeable units are effectively insignificant, the Lower Elk Point Group above the Basal Red Beds has been termed the Lower Devonian aquiclude system. It ranges in thickness up to 375 m (figure 27); the western and southeastern margins are depositional, whereas the eastern boundary is the result of salt solution.

Hydrodynamic information is not available from the thin and confined Ernestina Lake aquifer, lying between the Lotsberg and Cold Lake halite beds. The thinness, lithology, and position of this aquifer suggest that it is not likely to have any significant impact on the overall fluid flow system. Hydraulic parameters for the halite beds used in the numerical modelling have been derived from laboratory measurements reported in the literature (Gloyna and Reynolds 1961).

Winnipegosis aquifer system

The Contact Rapids Formation at the base of the Middle Devonian Upper Elk Point Group is the oldest aquifer which extends throughout the study area. It consists of argillaceous dolomite and dolomitic shales, ranging in thickness from 12 to 100 m. Overlying this aquifer is the Winnipegosis Formation which ranges in thickness from 30 to 80 m but in the region in which reliable formation waters have been recovered, it is between 40 and 60 m thick. Figure 28a shows the combined thickness of these two aquifers. Salinity decreases northeastward from about 295 000 mg/L to 55 000 mg/L (figure 28b), with corresponding decreases in Cl (175 000 to 30 000 mg/L), Ca (4500 to 1250 mg/L), and Mg (1150 to 290 mg/L). Sulfate shows an opposite trend; values are in the range of 2000 to 2500 mg/L where the aquifer is overlain by the Prairie Formation halite and anhydrite, but increase sharply updip from the solution edge to more than 5000 mg/L (figure 28d). Bicarbonate isoconcentration contours have an approximately east-west trend with values less than 200 mg/L in the south, and increasing to nearly 400 mg/L beyond the solution edge of the Prairie Formation (figure 28d). All these trends are consistent with an origin of the dissolved components from dissolution of halite and anhydrite.

Based on the results of about 20 drillstem tests from both the Contact Rapids and Winnipegosis aquifers, freshwater hydraulic heads range from 432 to 562 m in the study area. The flow is northwestward in the western part and changes progressively to the northeast in the central and eastern parts (figure 28c). In the eastern half of the study area, some drillstem tests in the Contact Rapids Formation yield similar hydraulic parameters to those in the Winnipegosis aquifer. Evidence of hydraulic continuity between these two aquifers is illustrated in figure 29; hence, the Contact Rapids aquifer and the Winnipegosis

aquifer are combined into the Winnipegosis aquifer system, which ranges in thickness between 40 and 270 m (average 120 m).

Nineteen bottomhole temperatures were measured in the Contact Rapids Formation in the Saskatchewan portion of the study area (figure 30). The values range between 19°C and 33°C for depths between 350 m and 1045 m. There is a general southwest to northeast decrease in temperature; the apparent temperature increase from the center of the region toward the north is dictated by a single data point (Tp 65 R 22 W3M), and because this feature is not seen in other temperature distributions higher up in the succession, it should be viewed critically.

Prairie aquiclude

The Prairie Formation halite and anhydrite overlie the Winnipegosis aquifer in the western two-thirds of the study area and comprise one of the major aquicludes. Where not subject to solution by meteoric water this aquiclude is 120 to 160 m thick (figure 31). Table 3 shows the composition of the raw brine produced by artificial solution of the Prairie Formation halite and anhydrite at the Lindberg salt plant.

Nine bottomhole temperature values are recorded in the Prairie Formation, most of them clustered in the southwest corner of the study area. Temperatures range between 24°C at 566 m depth in the north-center of the study area, and 40°C at 1325 m depth in the southwest.

Dawson Bay "aquifer"

The sedimentary rocks overlying the Prairie Formation comprise the First Red Beds-Watt Mountain clastic interval and are generally less than 25 m thick throughout the Cold Lake study area, although there are isolated regions up to 150 m. Included in this interval is the Dawson Bay "aquifer", which is commonly a dolomitized argillaceous limestone with much of the upper part of the carbonate now filled with halite (Grayston et al. 1964, fig. 5-7). As a result, only one reliable formation water has been recovered from this aquifer (table 3); this sample came from an area still underlain by the Prairie Formation halite in the zone subject to solution effects, and its composition reflects this situation and is similar to formation waters in the underlying Cambrian, although somewhat less saline. No drillstem tests or core data are available for this unit.

Measured temperature values at the top of the Elk Point Group above the Prairie Formation vary between 20°C at 600 m in the northeast and 48°C at 1280 m in the southwest. The 26 values scattered over the entire area produce a temperature distribution generally correlated with the stratigraphic dip (figure 32).

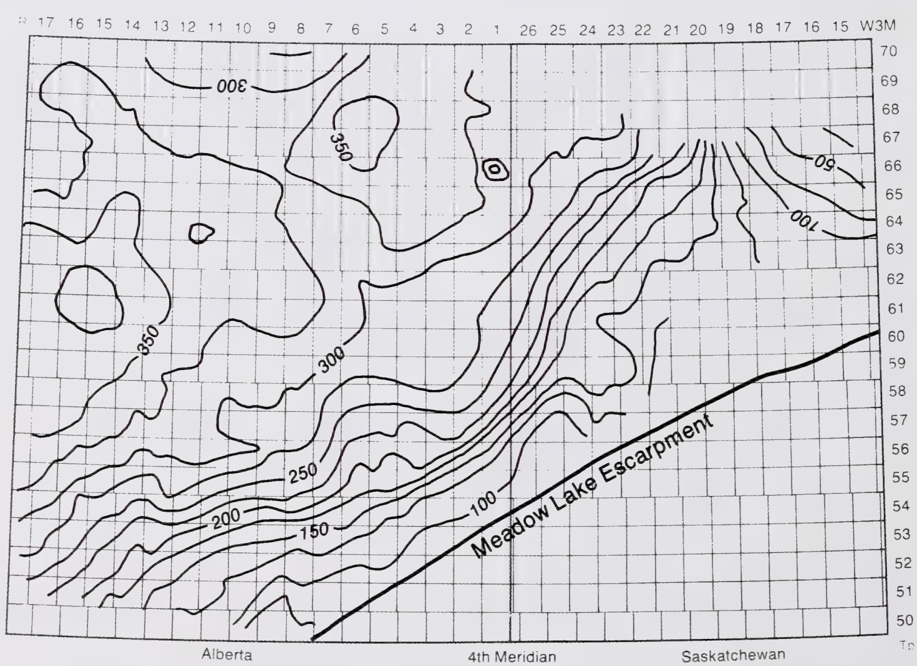


Figure 27. Isopachs of the Lower Devonian aquiclude system (contour interval 50 m).

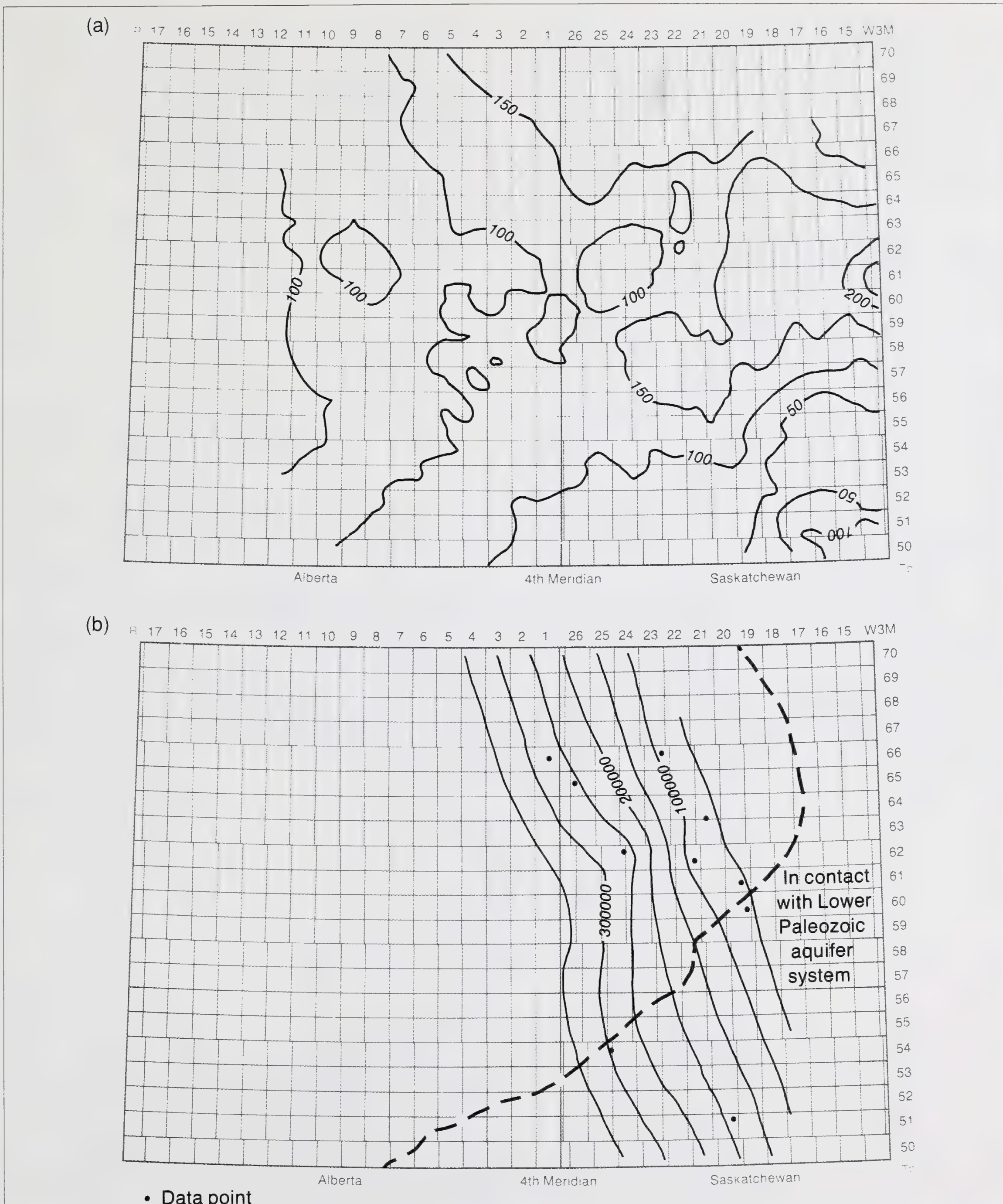


Figure 28. Winnipegosis aquifer system hydrogeology. (a) Isopachs (contour interval 50 m); (b) Salinity (mg/L) of formation waters; (c) Potentiometric surface; (d) Relation of SO_4 and HCO_3 in formation waters.

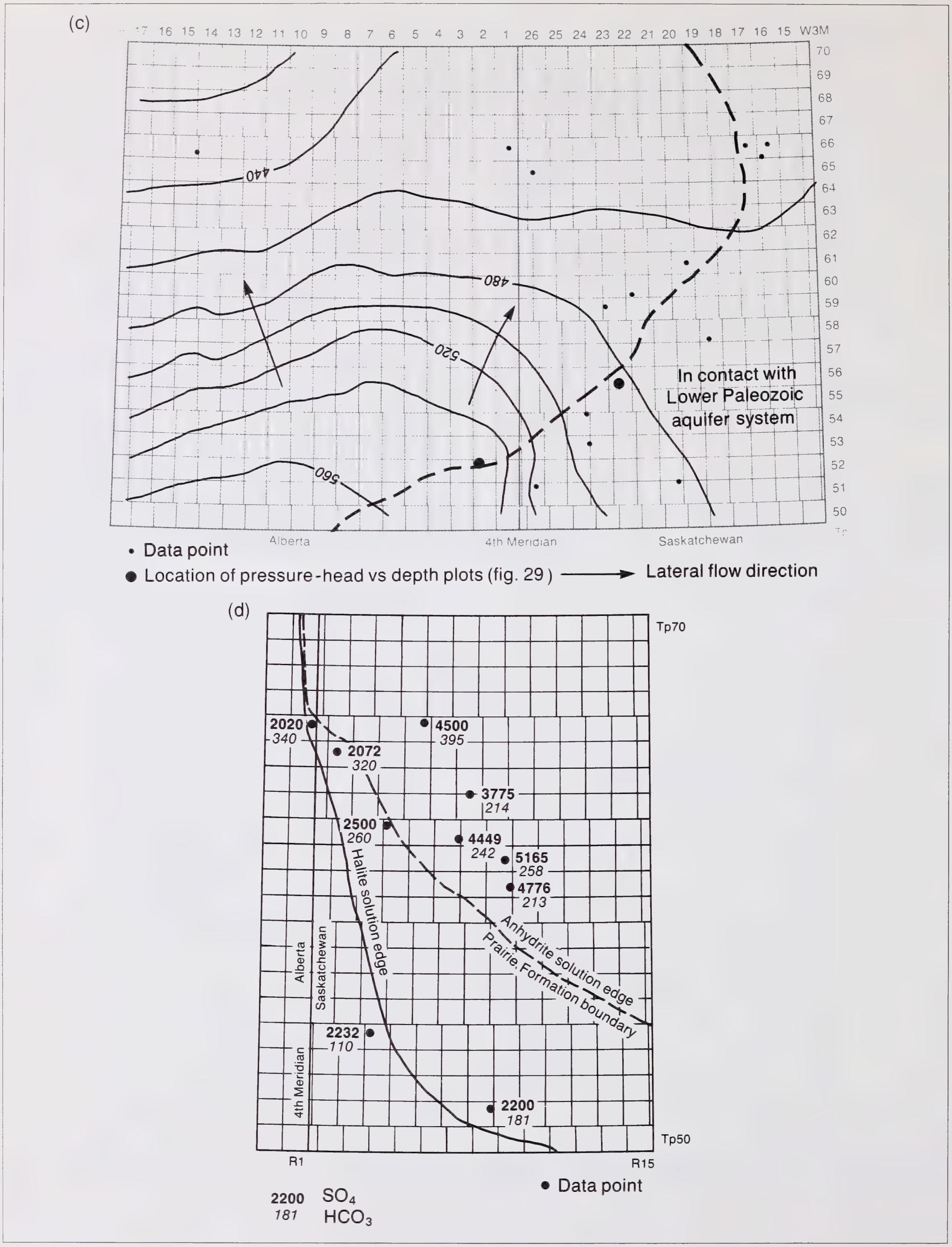


Figure 28. (continued)

Table 3. Chemical composition (mg/L), physical properties and production data for raw brine produced by artificial solution of the Prairie Formation halite at the Lindberg salt plant and a formation water from the Dawson Bay aquifer.

Stratigraphic unit	Prairie aquiclude*	Dawson Bay aquifer
Location	3-26-56-5-W4M	2-11-50-20-W3M
Depth (m)	901.6-933.6	816.6-828.8
Source	Plant inlet line	DST 1
Recovery	-	292.6 m sw
Na (diff.)	136 642	58 069
Ca	1 838	4 290
Mg	666	1 555
Cl	213 366	97 500
HCO_3	177	56
SO_4	3 221	5 600
TDS (calc.)	355 975	167 041
pH (laboratory)	7.2	6.8
Density (15.56°C)	1.209	1.113
Resistivity (23.33°C)	0.026	0.05

*Br = 65 mg/L; I = 0 mg/L; sw = salt water

Beaverhill Lake aquifer system

The Middle Devonian First Red Beds-Watt Mountain clastic interval is overlaid by carbonates of the Middle/Upper Devonian Beaverhill Lake Group and the Upper Devonian Cooking Lake and Leduc Formations. Although there is little information on the hydrogeology of the latest Middle Devonian rocks (see Dawson Bay "aquifer"), the stratigraphic position of all these aquifers between the underlying Prairie aquiclude and the overlying Ireton aquitard means that they can be grouped into the Beaverhill Lake aquifer system. Where this aquifer system has been preserved from erosion beneath the Ireton aquitard, thicknesses range from about 300 m to more than 500 m (figure 33a). East of the limit of the Ireton aquitard as little as 100 m remains in the Cold Lake study area, and here this aquifer system is in hydraulic continuity with the overlying Lower Cretaceous McMurray and Mannville aquifers. This hydraulic continuity is demonstrated at two locations by the plots in figures 34a and 34b; in addition, the vertical flow is downward (see also figure 34c).

Previous studies of basin-wide flow in the Western Canada Sedimentary Basin (Hitchon 1969a), including a potentiometric surface of the Beaverhill Lake aquifer (Hitchon 1969b, fig. 1) have shown that this aquifer is in the regional flow regime. The distribution of Cl (Hitchon 1964, fig. 15-15) and Ca and Mg (Hitchon and Holter 1971, figs. 14 and 15) is consistent with the regional trends and gradients on the potentiometric surface. Superimposed on the regional trends is an area of formation waters with Cl generally greater than 200 000 mg/L, Ca greater than 60 000 mg/L, and Mg greater than 9000 mg/L, all of which are associated with an evaporite-carbonate sequence in south-central Alberta. As expected from the association with evaporites, these very saline formation waters have high contents of Br and very low contents of I (Hitchon et al. 1977, fig. 3 and table 4).

The Cold Lake study area lies immediately north and adjacent to the region with the very saline formation waters; that is, it is structurally updip and hydraulically downflow. Accordingly, highest salinities (about 200 000 mg/L) in the Beaverhill Lake aquifer system are found in the extreme south-central part of the

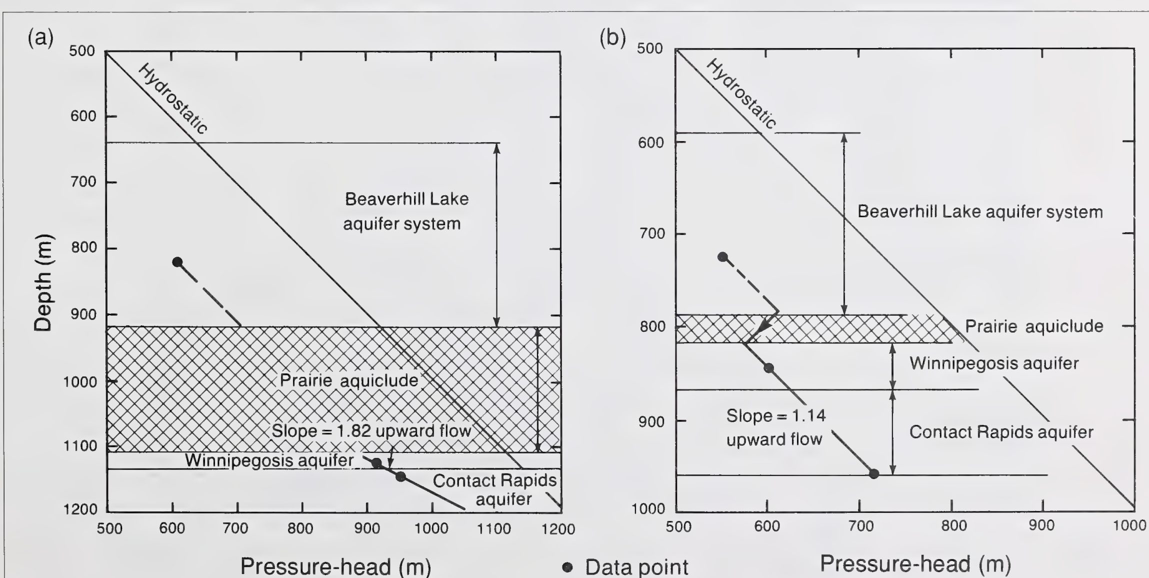


Figure 29. Vertical hydraulic continuity in the Winnipegosis aquifer system. (a) At well location 14-29-52-02-W4M; (b) At well location 12-10-56-23-W3M.

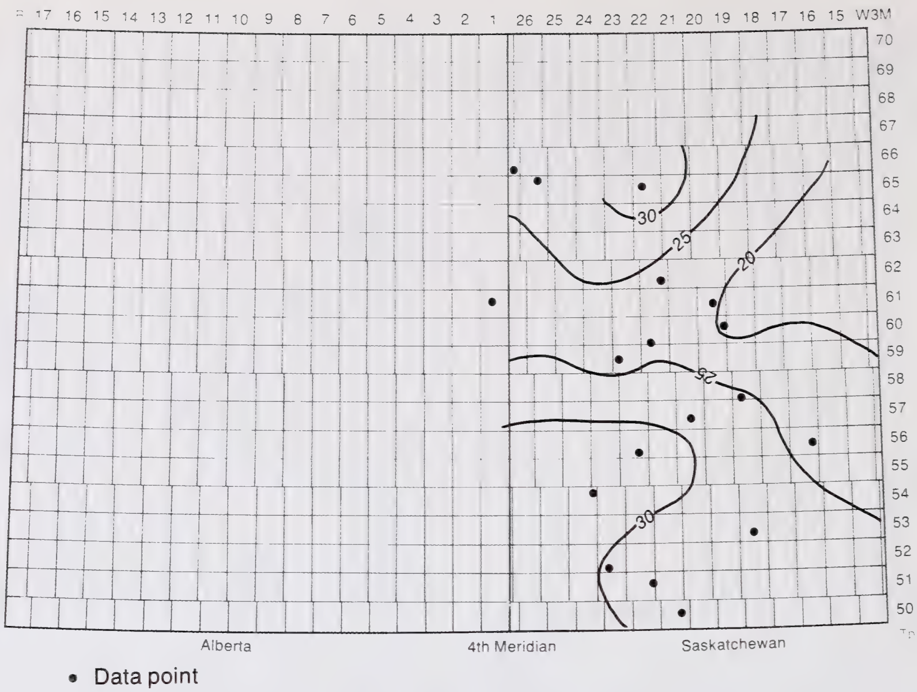


Figure 30. Temperature distribution in the Contact Rapids aquifer (5°C isotherms).

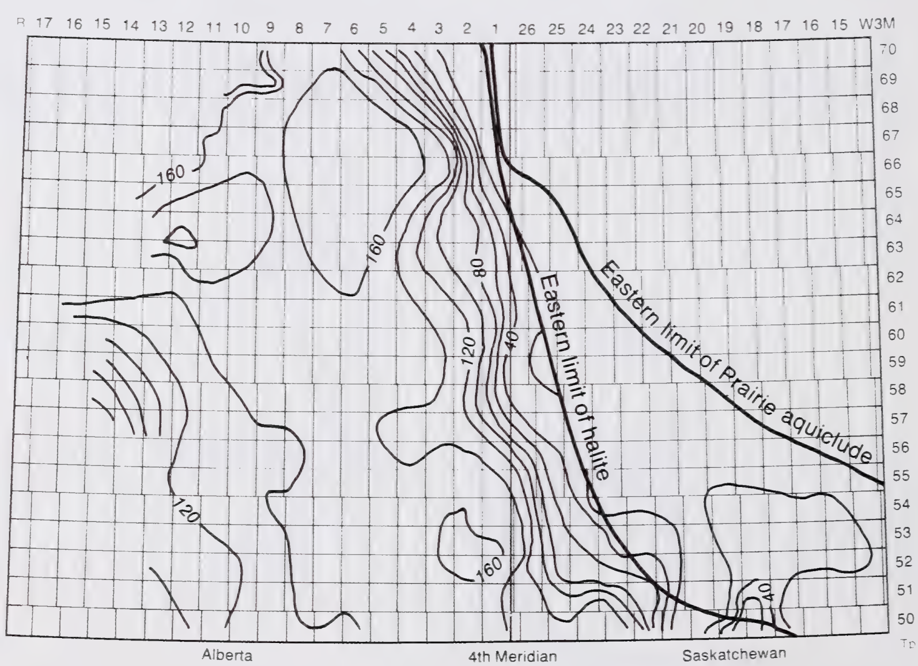


Figure 31. Isopachs of the Prairie aquiclude (contour interval 20 m).

Table 4. Chemical composition (mg/L), physical properties and production data for a formation water from the Leduc aquifer.

Location	2-26-55-15-W4M
Depth (m)	662.0-663.5
Source	DST 18
Recovery	91 m gassy sw
Na (diff.)	44 102
Ca	560
Mg	261
Cl	69 500
HCO_3	133
SO_4	244
TDS (calc.)	114 800
pH (laboratory)	8.4
Density (15.56°C)	1.020

sw = salt water

study area, and the salinity decreases rather uniformly and gradually toward the northeast where values of about 20 000 to 50 000 mg/L are found in the region where the Beaverhill Lake Group subcrops beneath the Lower Cretaceous Mannville Group (figure 33b). There are corresponding decreases in the contents of Cl (150 000 to 10 000 mg/L), Ca (20 000 to 1000 mg/L), and Mg (4000 to 250 mg/L). Isoconcentration contours for HCO_3 and SO_4 are more irregular and difficult to interpret; there is a tendency for low HCO_3 (≈200 mg/L) and high SO_4 (1000 to 2000 mg/L) in formation waters from the part of this aquifer system that is overlaid by the Ireton aquitard, with higher values for HCO_3 (up to 800 mg/L) and lower values for SO_4 (≈300 mg/L) in the eastern two-thirds of the study area. These trends for HCO_3 and SO_4 (as well as Na and Cl) are probably related to solution of evaporites (either from within the Beaverhill Lake Group or from the underlying Middle Devonian Prairie Formation), with dilution of the formation waters as they move updip from below the protective cover of the Ireton aquitard into regions with direct hydraulic connection with the Lower Cretaceous McMurray and Mannville aquifers (see figure 35a).

Included within the Beaverhill Lake aquifer system is the Leduc Formation reef at Willingdon (Tp 55 R 15 W4M). Formation waters were recovered from only one well penetrating the top of this reef complex, the best of which is shown in table 4. Salinity and Cl are similar to those of formation waters in the underlying Beaverhill Lake and Cooking Lake aquifers, but the contents of Ca, Mg, HCO_3, and SO_4 are all lower.

The Beaverhill Lake aquifer system is the first Paleozoic unit for which hydrodynamic information of good quality (31 values of hydraulic head) is distributed well enough to enable an unequivocal flow regime analysis. The lateral flow is regional, as already mentioned, with two flow components in the western half of the study area: in the southwest, the flow is southeastward and in the center and northwest areas, the flow is eastward. In the eastern half of the study area flow is mostly vertically downward from the Cretaceous aquifers, and the freshwater potentiometric surface becomes practically flat indicating a

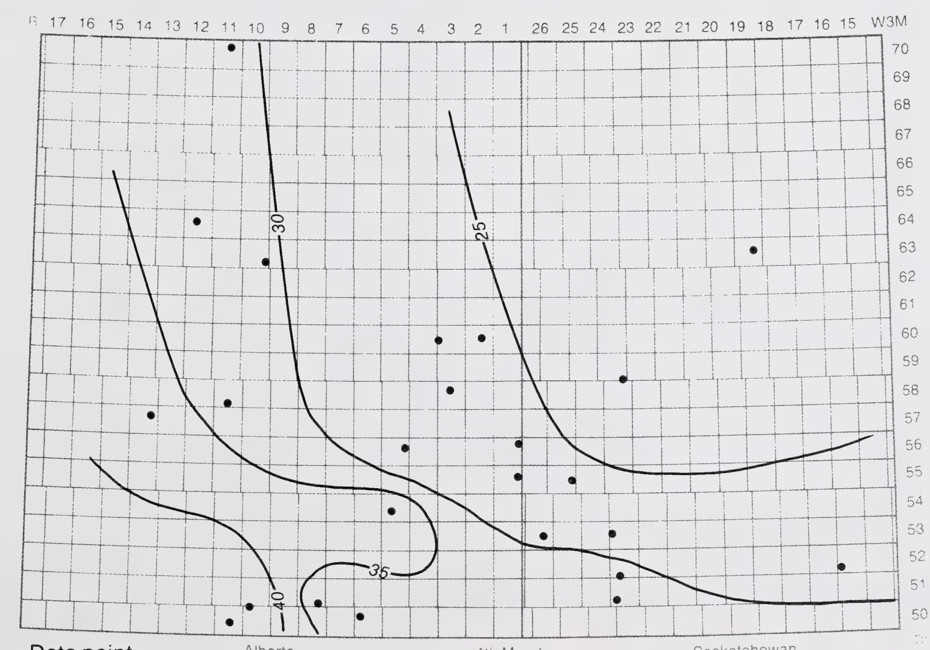


Figure 32. Temperature distribution at the top of the Elk Point Group (5°C isotherms).

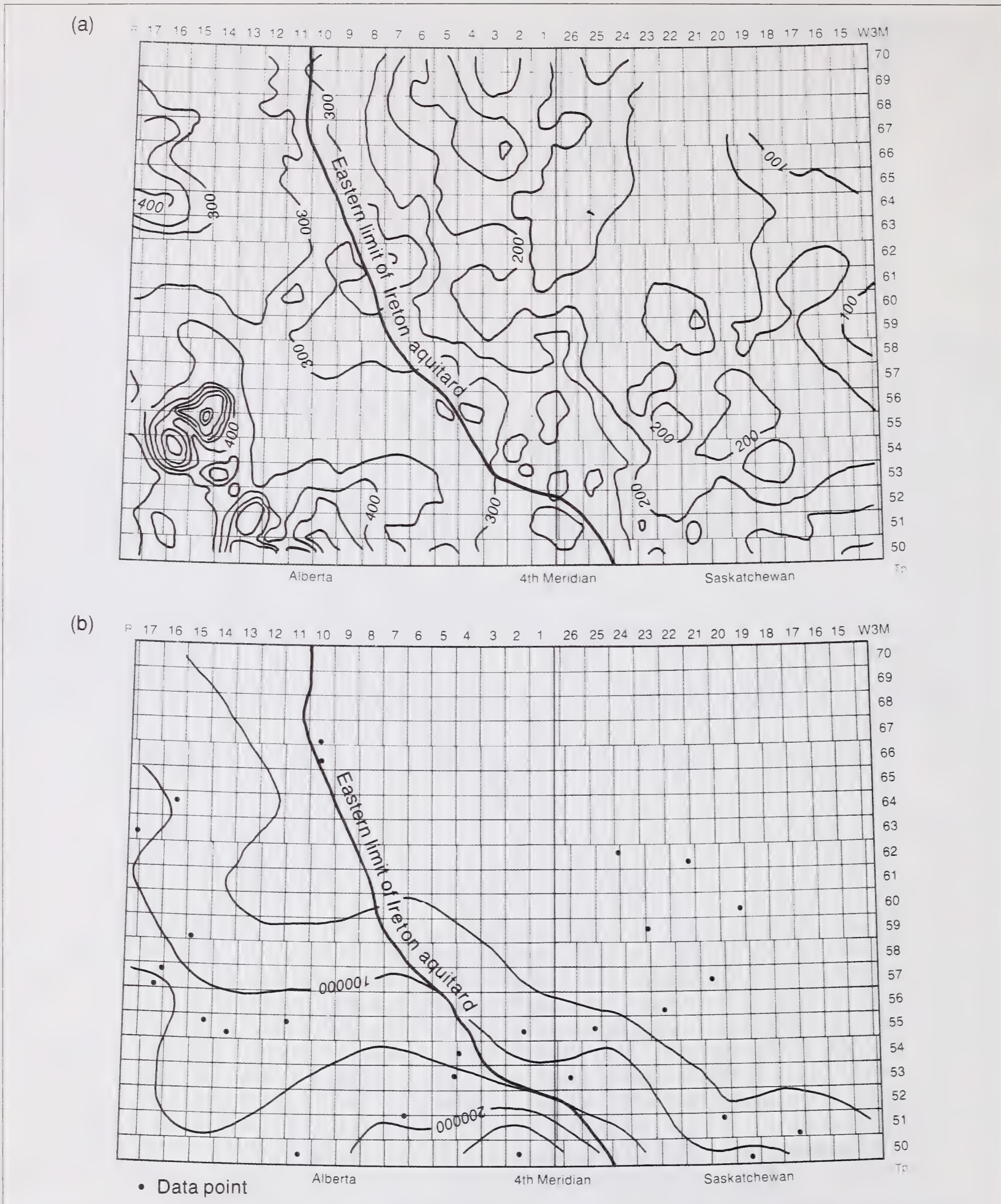


Figure 33. Beaverhill Lake aquifer system hydrogeology. (a) Isopachs (contour interval 50 m); (b) Salinity (mg/L) of formation waters; (c) Potentiometric surface; (d) Temperature distribution (5°C isotherms).

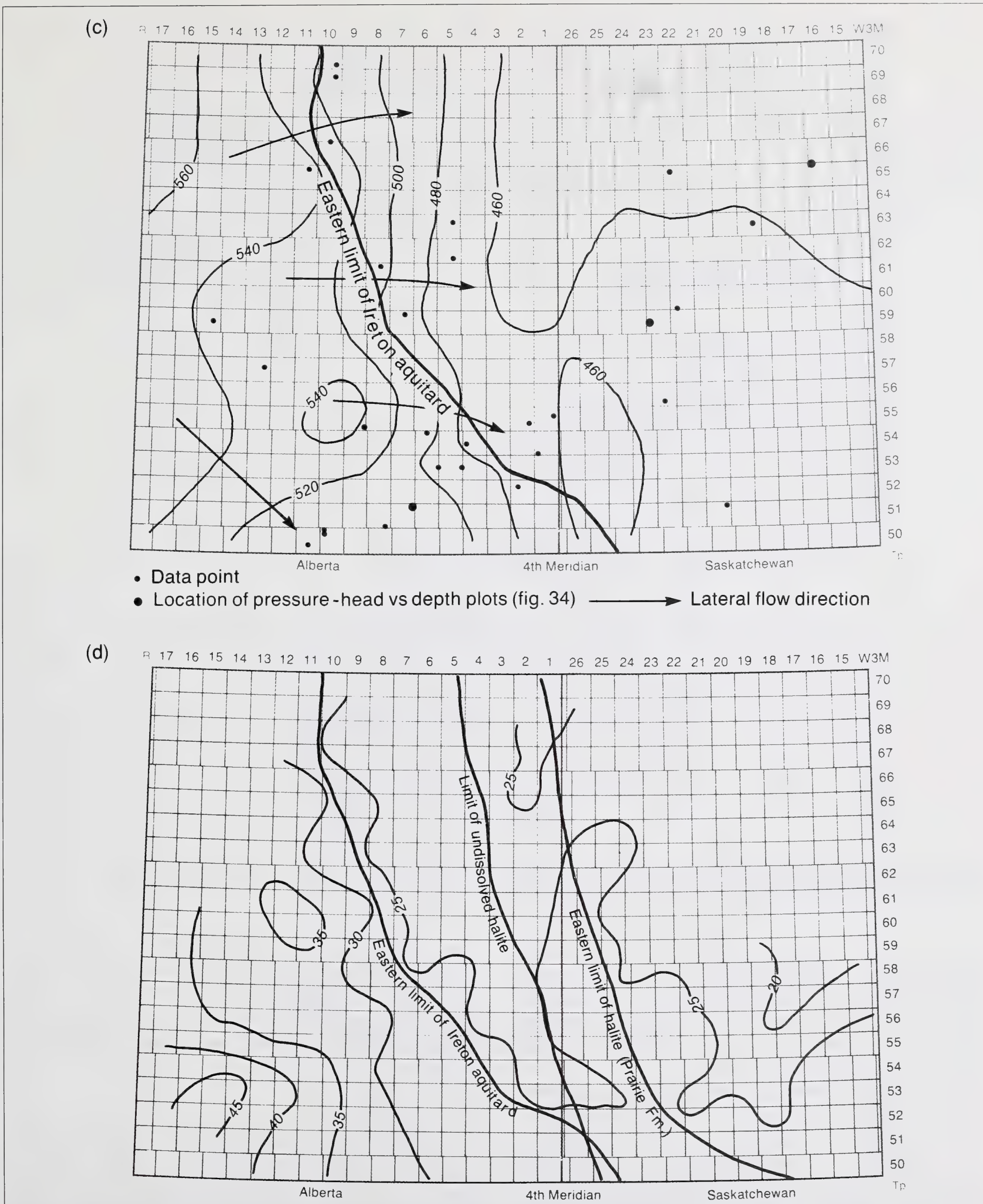


Figure 33. (continued)

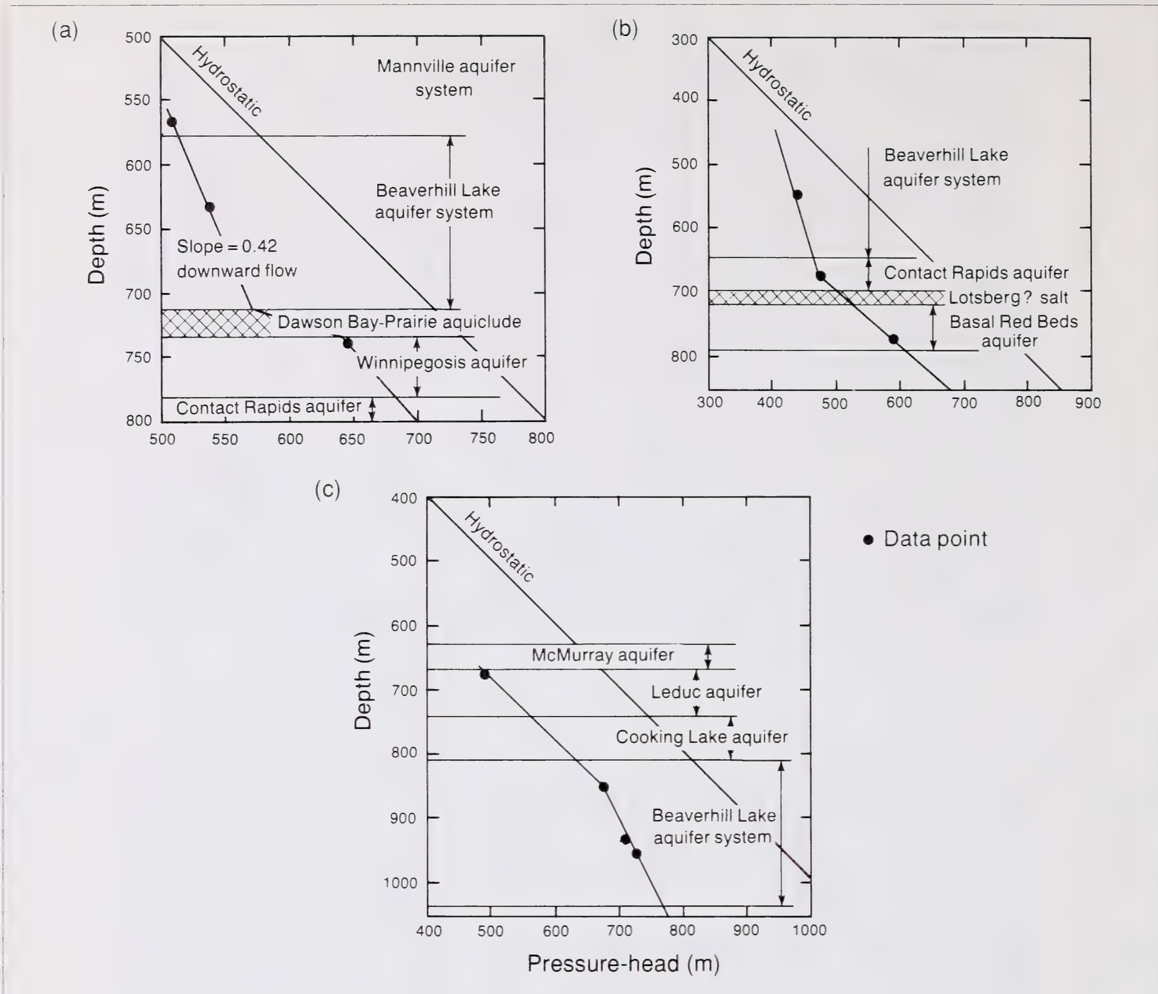


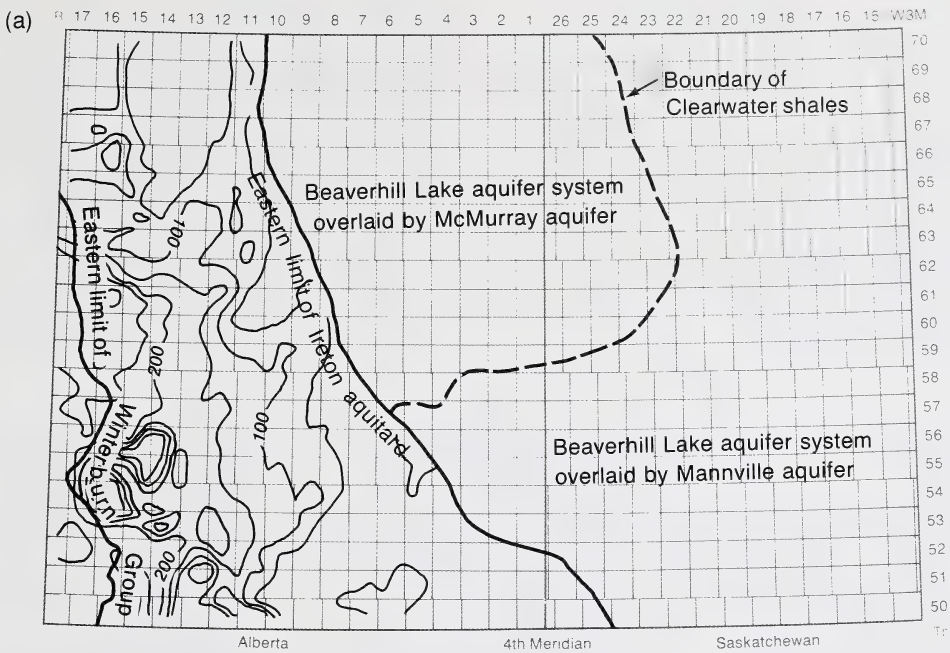
Figure 34. Cross-formational flow as illustrated by pressure-head vs depth plots in the Paleozoic. (a) At well location 7-19-59-23-W3M; (b) At well location 4-5-66-16-W3M; (c) At well location 13-36-51-07-W4M.

very slow lateral motion. The overall range of freshwater hydraulic head is between about 450 m in the northeast and 550 m along the western boundary of the study area. The salinity gradients are in general agreement with the trend of the hydraulic gradients (compare figures 33b and 33c).

Bottomhole temperatures were measured at 1221 locations in the Beaverhill Lake aquifer system, most of them in the upper part of the aquifer in the central third of the study area, generally right underneath the oil sand and heavy oil deposits. Figure 33d presents isotherms generally at the top of this aquifer system. The southwest-northeast trend of decreasing temperatures is again consistent with the dip of the aquifer, especially in the western third of the study area where the Beaverhill Lake Group is uneroded. In the central part, the 25°C isotherm follows the features at the top of the Beaverhill Lake Group, the "higher" temperatures being coincident with the structural low which delineates the collapse of Beaverhill Lake Group strata due to salt solution of the underlying Prairie Formation.

Ireton aquitard

The argillaceous lime mudstones of the Ireton Formation occur only in the western third of the Cold Lake study area, and along part of the southern boundary. Except for a narrow band on the western margin of the study area, where it is conformably overlaid by carbonates of the Winterburn Group, it is overlaid unconformably by Lower Cretaceous Mannville Group rocks. Maximum thickness of this aquitard is about 250 m



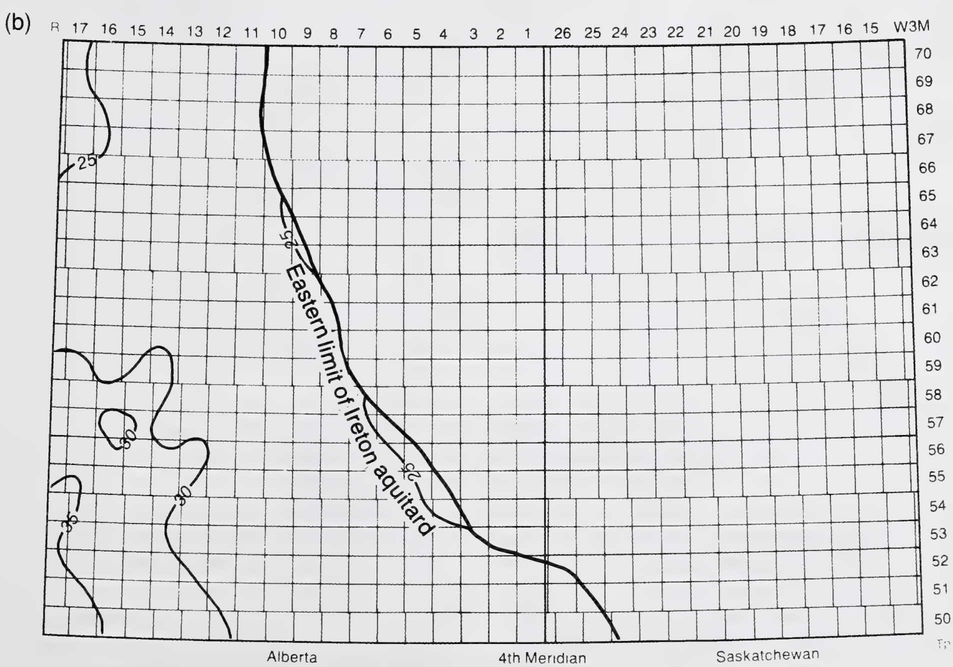


Figure 35. Ireton aquitard. (a) Isopachs including the thin Camrose Tongue aquifer (contour interval 50 m); (b) Temperature distribution (5°C isotherms).

(figure 35a), including the thin Camrose Tongue. A previous study (Basin Analysis Group 1985) estimated the vertical hydraulic conductivity of the Ireton aquitard to be $2x10^{-9}$ m/d, which would be classed as a tight aquitard.

More than 3050 wells which penetrate the top of the Ireton aquitard record bottomhole temperatures, which range between 19°C at a depth of 190 m, and 45°C at a depth of 1230 m. The general trend of temperature increase follows the stratigraphic updip from northeast to southwest (figure 35b). Only in the northwest corner of the area is this pattern altered by the presence of Grosmont carbonates, which are characterized by higher thermal conductivity.

Camrose Tongue aquifer

The southwest corner of the Cold Lake study area includes the northeastern margin of the Camrose Tongue dolomite, a thin (less than 10 m) aquifer within the Ireton Formation (figure 36a). This aquifer lies about 10 to 20 m below the top of the Ireton aquitard and about 150 m above its base. As a result, formation waters in the Camrose Tongue aquifer tend to resemble those in the overlying aquifers rather than those in the Beaverhill Lake aquifer system. Salinities are in the range 80 000 mg/L in the south to less than 40 000 mg/L in the north (figure 36b), with east-west oriented isoconcentration contours. Corresponding ranges for other components are Cl (45 000 to

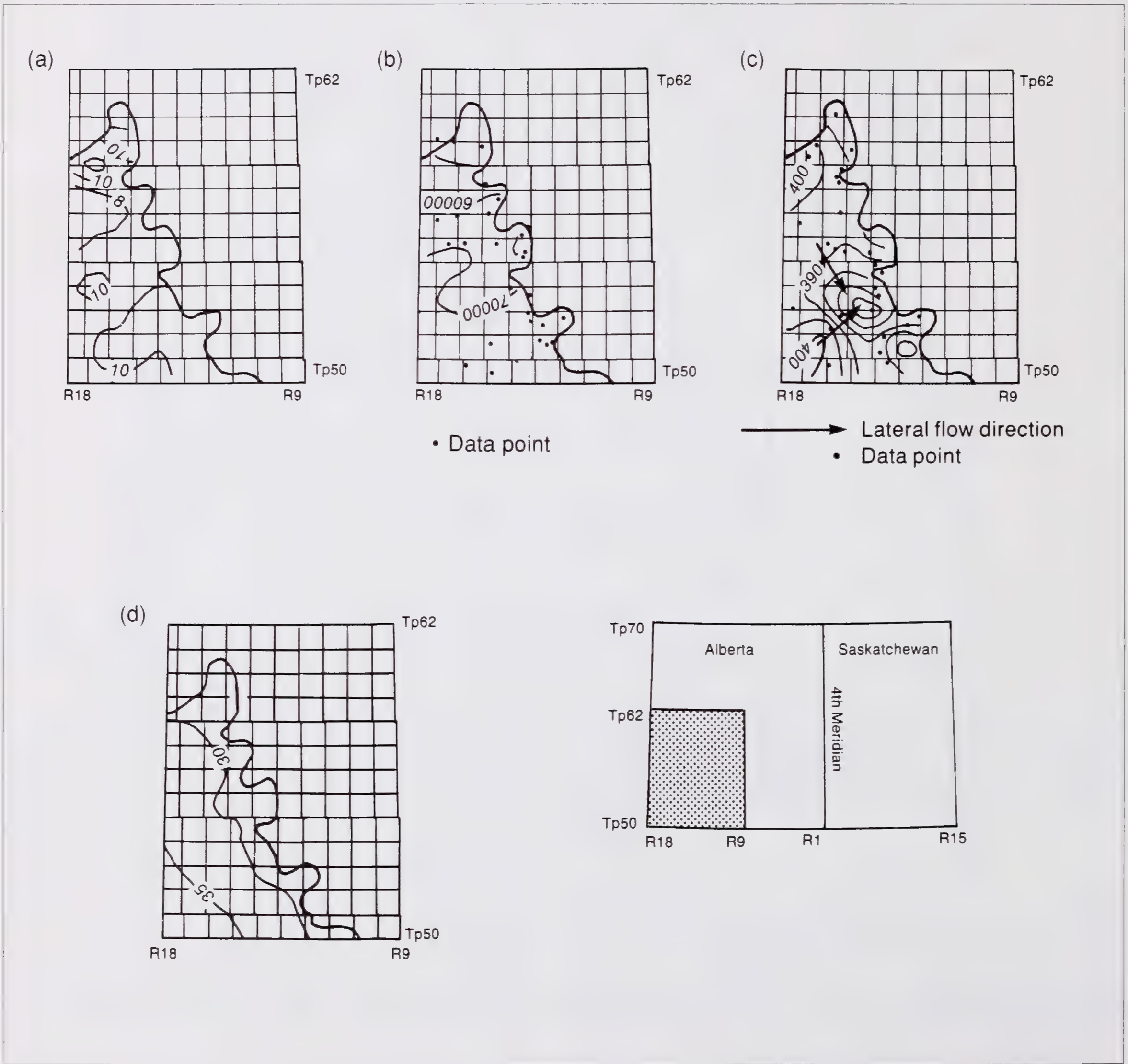


Figure 36. Camrose Tongue aquifer hydrogeology. (a) Isopachs (contour interval 2 m); (b) Salinity (mg/L) of formation waters; (c) Potentiometric surface; (d) Temperature distribution (5°C isotherms).

25 000 mg/L), Ca (3000 to 1250 mg/L), and Mg (1000 to 500 mg/L). Sulfate is generally about 50 mg/L without any obvious regional trend. The content of HCO_3 decreases from about 600 mg/L along the western margin of the study area to just over 200 mg/L along the formation boundary; that is, the isoconcentration contours trend north-south, at right angles to those for salinity, Cl, Ca, and Mg.

The lateral flow, although in agreement with the major hydrochemical gradients, also has an eastward component (see figure 36c) that could be responsible for the anomalous direction of the HCO_3 gradient. The eastward flow could also be related to downward flow from the Winterburn aquifer. There is insufficient hydrodynamic information for this unit in the study area to be more precise about flow directions. As shown on figure 37, there is a decrease in hydraulic head of 30 m over a distance of about 12 km at the northern margin of the Camrose Tongue aquifer between this aquifer and the Grosmont aquifer.

Temperature distribution in the Camrose Tongue aquifer is defined by 131 bottomhole temperature values, and increases very uniformly with the dip of the aquifer (figure 36d).

Grosmont aquifer

The Grosmont Formation is a dolomitized platform carbonate which is approximately coeval with the Ireton Formation. It extends 500 km south from outcrops along the Peace River to the northwest corner of the Cold Lake study area, where it ranges in thickness from 50 to 100 m (figure 38a).

Early studies of the potentiometric surfaces of the individual Woodbend Group carbonates in the Western Canada Sedimentary Basin demonstrate the dominant regional flow within the carbonate complexes, with the lowest hydraulic heads being found in the Grosmont Formation (Hitchon 1969b, fig. 2). Pressure vs elevation, temperature vs depth, and temperature vs elevation profiles confirm the continuous flow system between the Rimbey-Meadowbrook reef chain and the updip Grosmont Formation carbonate complex (Hitchon 1984, figs. 15 to 17). These trends are reflected in the distribution of Cl in the formation waters (Hitchon 1964, fig. 15-17), and also Ca and Mg (Hitchon and Holter 1971, figs. 8 and 9), and to a lesser extent Br (Hitchon et al. 1977, fig. 2).

Like the formation waters in the Camrose Tongue aquifer to the south, the salinity decreases northward from about 35 000 mg/L to just under 15 000 mg/L (figure 38b). There are corresponding decreases in Cl (25 000 to 10 000 mg/L) and, less clearly, Ca (500 to 200 mg/L) and Mg (350 to 150 mg/L). Sulfate increases toward the northwest in the direction of the Hondo Formation anhydrites (Belyea 1964, fig. 6-16) which are interlayered within the Grosmont Formation. Bicarbonate is generally less than 1000 mg/L on the southern and eastern margins of the formation, and in-

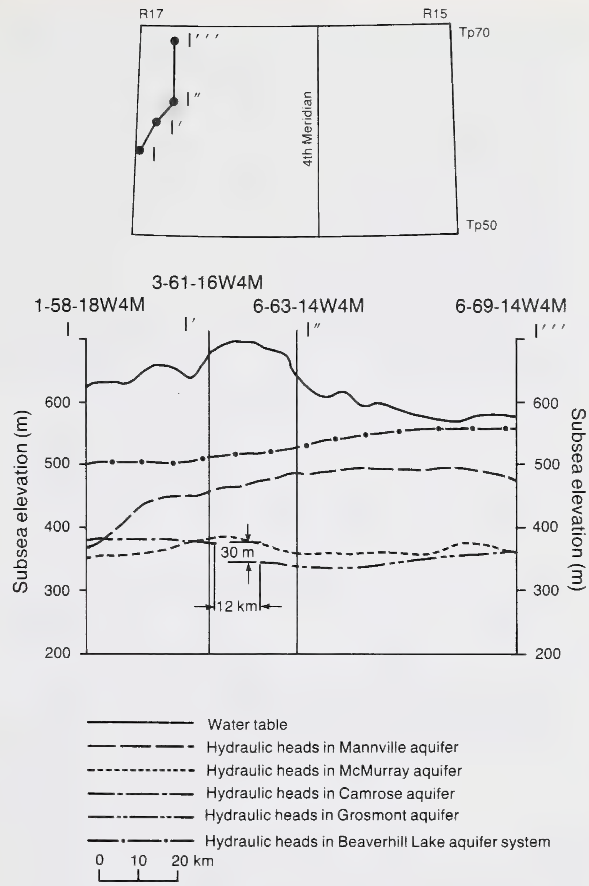


Figure 37. North-south cross section showing the hydraulic separation between the Camrose Tongue aquifer and the Grosmont aquifer.

creases to about 1250 mg/L in the northwest corner of the study area. Areally, the southern margin of the Grosmont aquifer and the northern extent of the Camrose Tongue aquifer are only 5 km apart. In general, formation water composition is similar in the extremities of these separate aquifers, which suggests hydraulic continuity through the thin intervening Ireton aquitard.

In the Grosmont aquifer, the lateral flow diverges in two directions (southeast and northeast) from a potentiometric high located at Tp 66 R 17 (figure 38c). Some of the lowest values of freshwater hydraulic head for the study area are found in this aquifer (between 300 m and 350 m). The hydraulic conductivity (0.017 m/d on average) is similar to that of the Camrose Tongue aquifer (0.022 m/d on average).

Formation temperatures in the Grosmont aquifer (118 values) vary in a narrow range, most being about 25°C (figure 38d), without any obvious regional trend.

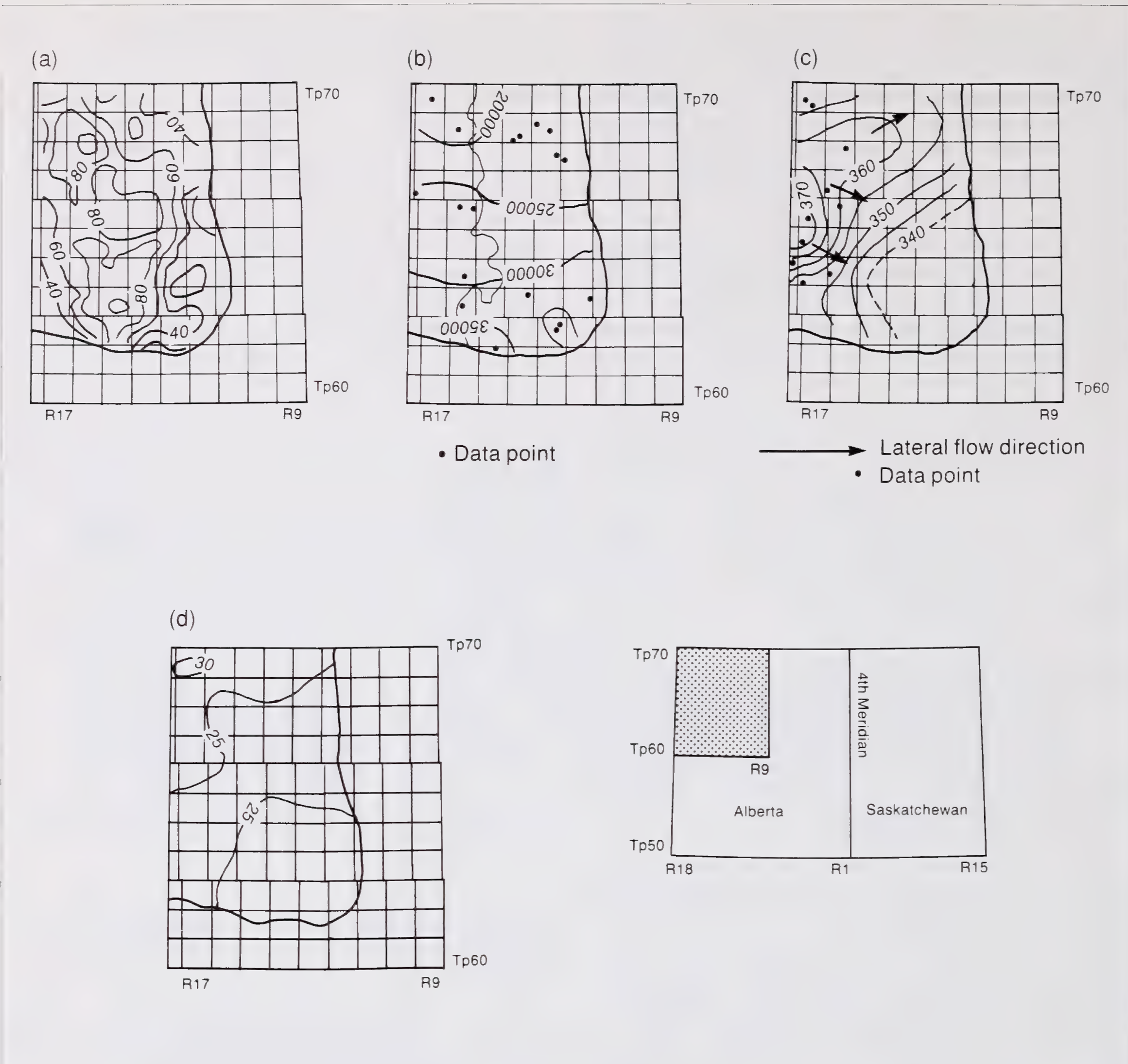


Figure 38. Grosmont aquifer hydrogeology. (a) Isopachs (contour interval 20 m); (b) Salinity (mg/L) of formation waters; (c) Potentiometric surface; (d) Temperature distribution (°C).

Winterburn aquifer

In the Cold Lake study area the Upper Devonian Winterburn Group consists of an eroded remnant along the western boundary, with a maximum thickness of about 50 m. Only eight reliable formation waters are available, with salinities decreasing northward from about 55 000 mg/L at Tp 57 to 25 000 mg/L at Tp 61. There are corresponding decreases in all other components except HCO_3, which exhibits an increase from 50 to nearly 800 mg/L over the same five townships. Insufficient hydrodynamic data and the marginal position of this aquifer in the study area preclude an analysis of the fluid flow. Fifty-four temperature data show an updip decrease in temperature from about 35°C to 25°C, consistent with the general pattern.

McMurray aquifer

In the Cold Lake study area the basal stratigraphic unit of the Cretaceous is the McMurray Formation, which is overlaid everywhere by the Clearwater Formation. In the northwestern half of the study area the basal unit of the Clearwater Formation is argillaceous; this serves to distinguish two hydrostratigraphic regions within the McMurray Formation: (1) the McMurray aquifer where the basal unit of the Clearwater Forma-

tion is argillaceous; and (2) the remainder, designated as part of the Mannville aquifer. From west to east the McMurray aquifer rests on successively older Upper Devonian rocks which comprise the Winterburn and Grosmont aquifers, the Ireton aquitard, and the Beaverhill Lake aquifer system. The extreme eastern margin of the McMurray aquifer is east of the solution edge of the Prairie Formation halite and hence there is hydraulic continuity in this area between the McMurray aquifer, the Beaverhill Lake aquifer system, and the Winnipegosis aquifer; unfortunately, reliable formation water analyses were not recovered from drillstem tests in this critical area. The McMurray aquifer ranges up to 120 m thick (figure 39a).

Isoconcentration contours for components in the formation waters have a general east-west orientation, with salinity decreasing northward from 60 000 mg/L to 10 000 mg/L (figure 39b), and corresponding decreases for Cl (35 000 to 5000 mg/L), Ca (1000 to less than 250 mg/L), and Mg (700 to less than 100 mg/L). Bicarbonate increases northward from about 400 to more than 1200 mg/L. Sulfate is generally less than 100 mg/L with no clearly defined trends.

Where the McMurray aquifer and Beaverhill Lake aquifer system are in contact, both the directions and gradients of the respective isoconcentration contours are similar, with generally lower values in the McMurray aquifer by only 10 000 mg/L for salinity, and corresponding decreases for Cl (5000 mg/L), Ca (500 mg/L), Mg (50 mg/L), HCO_3 (100 mg/L), and SO_4 (≈50 mg/L). These facts strongly suggest excellent hydraulic continuity between these aquifers in the region of contact. Similar relations are found where the McMurray aquifer overlies the Grosmont and Winterburn aquifers. In the region where the McMurray aquifer and Beaverhill Lake aquifer system are separated by the Ireton aquitard (which is about 100 m thick), salinities vary by as much as 40 000 mg/L, with corresponding differences for the other components. Although data are sparser in the Beaverhill Lake aquifer system, the broad trends and isoconcentration gradients for the two aquifers are similar; for example, the southwest trending re-entrant on many formation water composition maps associated with the Leduc Formation reef complex at Willingdon can be seen on both sets of maps. This suggests that the Ireton aquitard is not tight here, and that the effects of flow in the underlying Beaverhill Lake aquifer system are reflected in the overlying McMurray aquifer.

Based on 152 good quality drillstem tests, the freshwater hydraulic heads in the McMurray aquifer range between 320 m (in the northwest part of the study area) to 490 m close to the southeastern boundary of the aquifer. The potentiometric surface of the McMurray aquifer (figure 39c) shows that the influence of the underlying Grosmont aquifer dominates the lateral flow in this unit: the 375 m and 400 m contours are effectively coincident with the eastern boundary of the Grosmont carbonate platform and all of the lateral flow is focused toward the area of overlap between the two aquifers.

Because Cretaceous strata have a shallower southwestern dip than do Paleozoic strata, the isotherms in the Cretaceous aquifers do not show such a clear relation to the dip as do the deeper units. Moreover, the porous medium is less homogeneous with respect to the solid matrix, fluid content, and saturation, therefore influencing the temperature distributions more through local variations in thermal conductivity. The measured temperatures in the McMurray aquifer (745 values) vary between 15°C at a depth of 430 m and 36°C at a depth of 720 m. A general trend can be discerned in the temperature distribution, with decreasing values from southwest to northeast (figure 39d); this trend is in strong contrast to the salinity and potentiometric surface trends. This feature can be explained if one takes into account the different mechanisms for heat and mass (solute) transport in this aquifer. The convection of heat by the formation waters is negligible (Pe less than 10^{-2}), therefore the temperature distribution is controlled by stratigraphy and lithology, decreasing updip (toward the northeast). The mass transport processes are controlled only by the flow of formation waters, therefore the salinity distribution shows a strong correlation with the potentiometric surface.

Clearwater aquifer

The arenaceous unit within the Clearwater Formation is defined as the Clearwater aquifer. It is thin (average 35 m) and is underlaid and overlaid by shales of the Clearwater Formation (figure 40a). The southern and eastern boundaries are depositional, marking the shoreline at this time in Cretaceous history. The northwestern margin is also depositional and represents the seaward extent of this sand body, to the north of which only Clearwater Formation shales are present. The composition of formation waters (represented by the salinity map, figure 40b), and the directions and gradients on the isoconcentration contours, are effectively the same as those in the underlying McMurray aquifer, indicating that the intervening lower Clearwater Formation shale is a weak (leaky) aquitard.

The lateral flow in the Clearwater aquifer (figure 40c), determined by 85 good quality drillstem tests, is similar to that in the McMurray aquifer (figure 39c) as confirmed by the hydrochemistry. The freshwater hydraulic heads vary between 350 and 480 m; the regional average hydraulic conductivity is 3.7×10^{-2} m/d.

In the lower Clearwater shale, the Clearwater sandstone, and the upper Clearwater shale there are 46, 71, and 65 bottomhole temperature values, respectively, but they are mostly clustered such that no trend analysis could be performed. The bottomhole

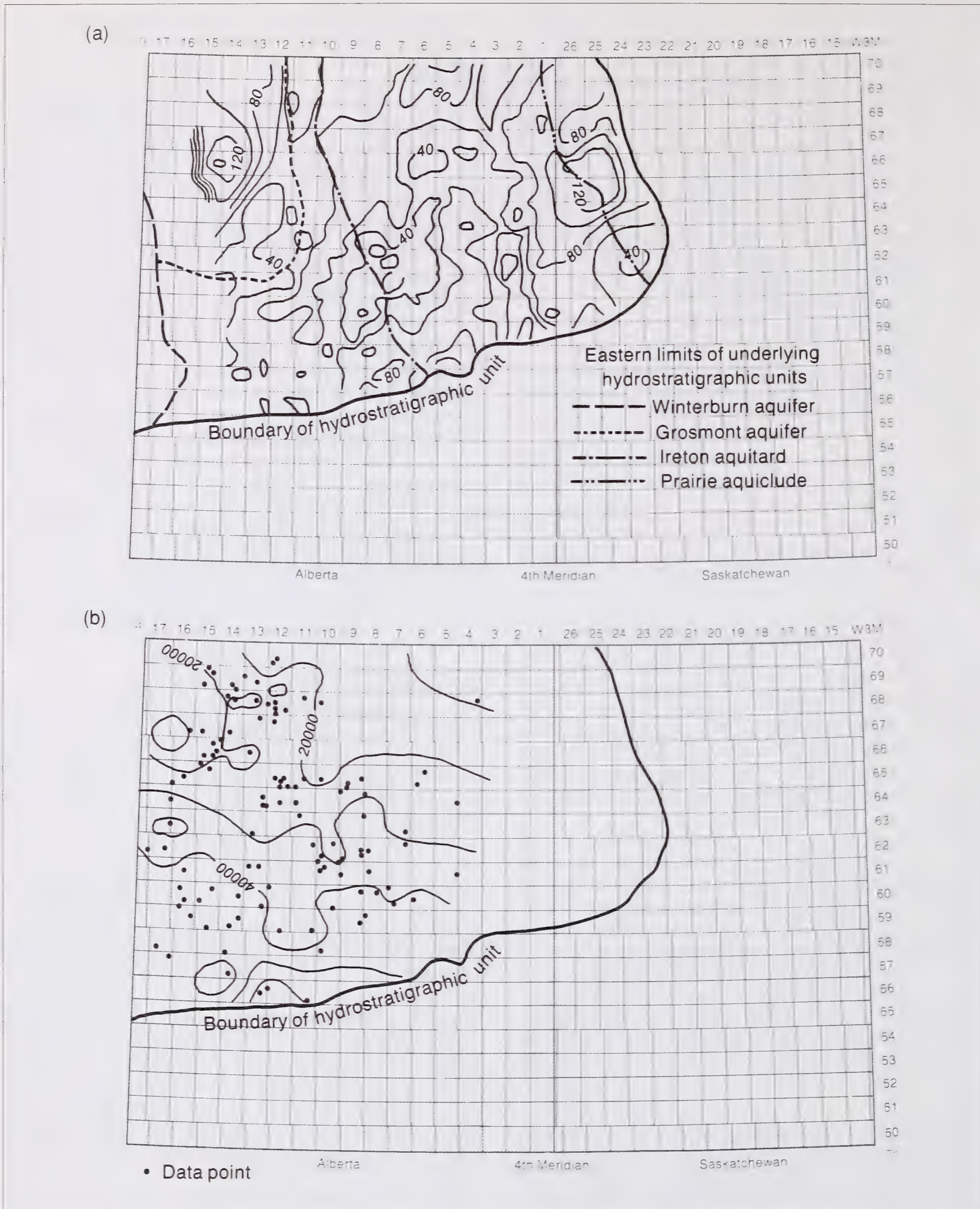


Figure 39. McMurray aquifer hydrogeology. (a) Isopachs (contour interval 20 m); (b) Salinity (mg/L) of formation waters; (c) Potentiometric surface; (d) Temperature distribution (5°C isotherms).

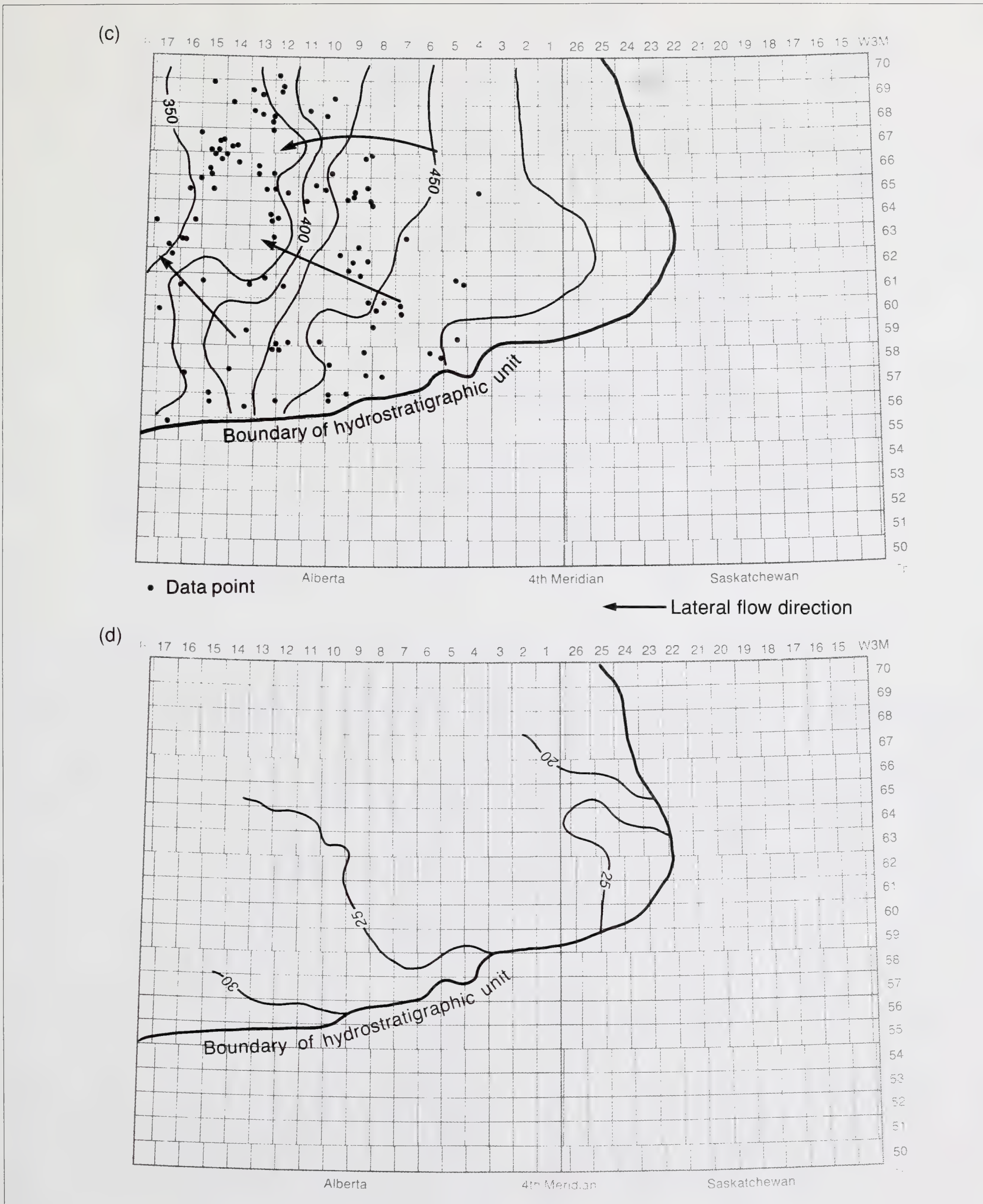


Figure 39. (continued)

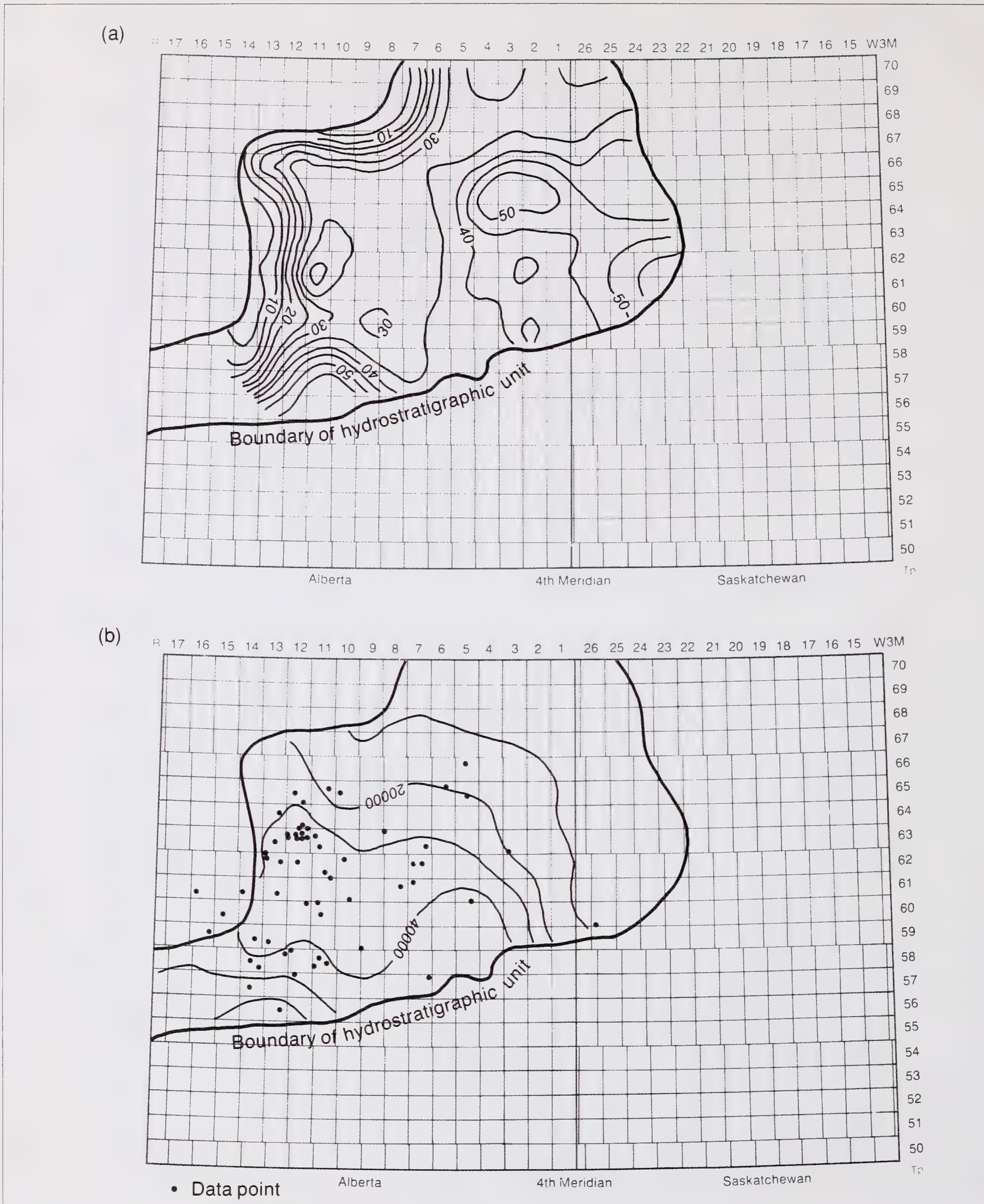


Figure 40. Clearwater aquifer hydrogeology. (a) Isopachs (contour interval 5 m); (b) Salinity (mg/L) of formation waters; (c) Potentiometric surface.

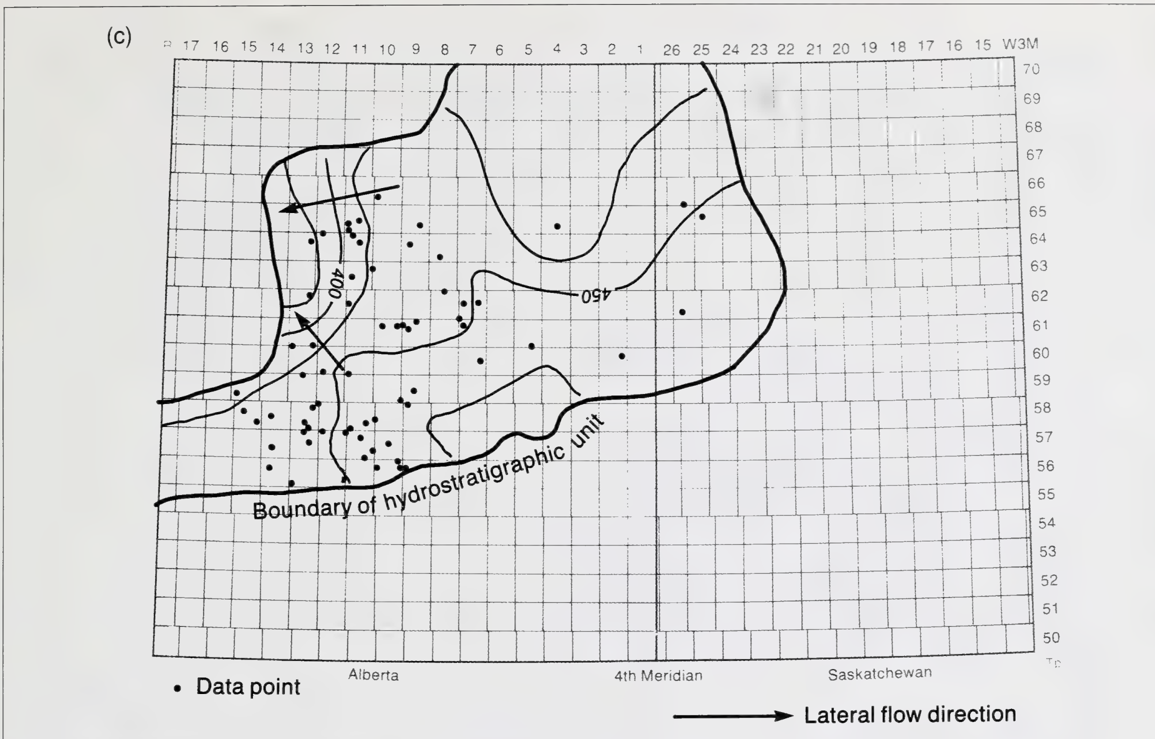


Figure 40. (continued)

temperatures range between 18°C and 31°C, for depths between 400 m and 715 m.

Mannville aquifer

Hydrostratigraphic units within the Lower Cretaceous Mannville Group have a complex geometric relation. Where the Clearwater Formation is present it is possible to distinguish both the McMurray aquifer and the overlying Clearwater Formation with its interbedded Clearwater aquifer. Mannville Group strata elsewhere in the Cold Lake study area have been designated as the Mannville aquifer and include within them oil sand aquitards. The strike cross section in figure 41 illustrates this complex geometric relation.

The Mannville aquifer extends throughout the study area with an average thickness of 200 m (figure 42a). Formation water analyses were essentially available only for Alberta and parts of the western border region of Saskatchewan. Salinity decreases from more than 60 000 mg/L in the south to less than 10 000 mg/L in the north (figure 42b), with corresponding decreases for Cl (40 000 to 5000 mg/L), Ca (2000 to less than 250 mg/L), and Mg (800 to less than 100 mg/L), and generally corresponding increases for HCO_3 (200 to 900 mg/L). Sulfate is usually less than 100 mg/L, without obvious regional trends; however, most of the isolated regions with SO_4 greater than 100 mg/L are confined to the region with salinities greater than 50 000 mg/L. Both isoconcentration trends and gradients are effectively identical with those in the underlying Clearwater and McMurray aquifers, and it seems clear that formation waters in the entire Mannville Group are part of one complex hydrostratigraphic unit with intervening leaky aquitards. In the region south of the southern limit of the Clearwater aquifer, which has up to 200 m of Ireton aquitard beneath the Mannville aquifer, comparison of formation waters with those in the Beaverhill Lake aquifer system shows salinity differences of about 40 000 mg/L, with corresponding differences for other components. This observation is consistent with that for the McMurray aquifer and, again, confirms that the Ireton aquitard is not leaky. Although there is a paucity of data from the Beaverhill Lake aquifer system, comparison of the chemistry of formation waters from this aquifer with those in the overlying Mannville aquifer where the Ireton aquitard is absent indicates very similar compositions (with the exception of SO_4), indicative of good hydraulic connection between the two aquifers.

Over most of the study area the freshwater potentiometric surface for the Mannville aquifer is “flat” indicating general vertical flow conditions. Outward lateral flow is observed on the western and southern edges of the study area (figure 42c); this trend is only

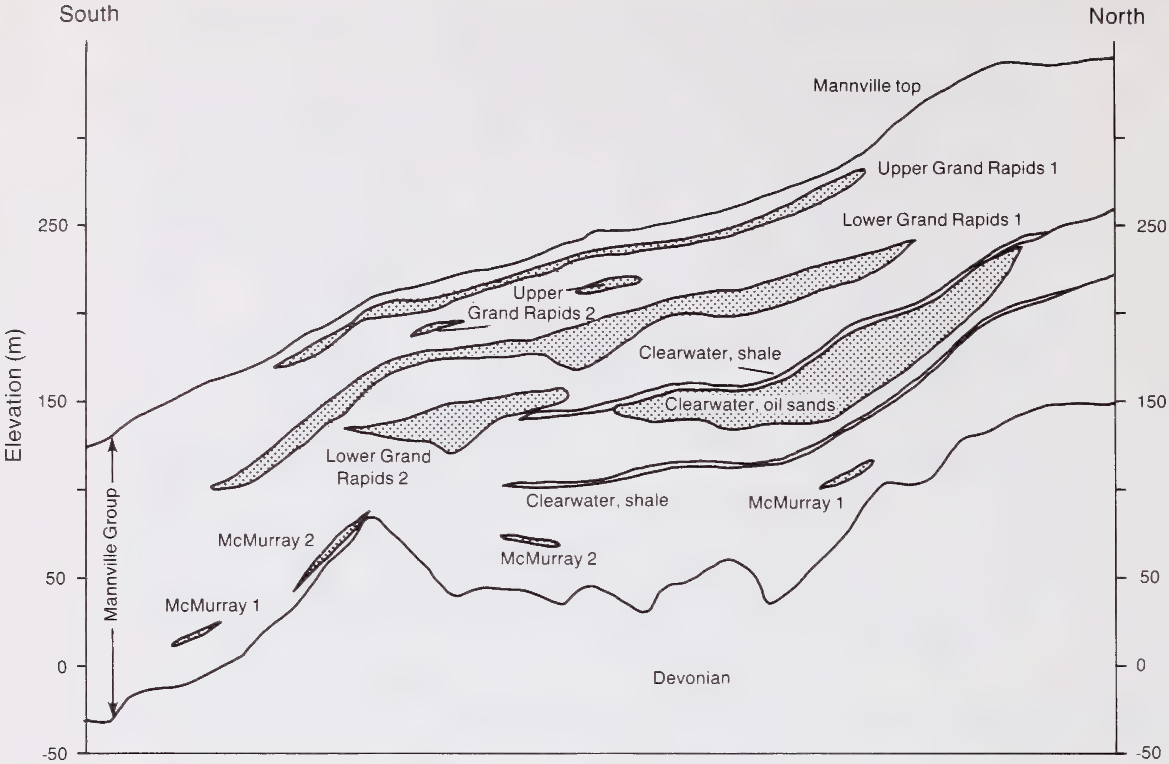


Figure 41. Diagrammatic strike cross section through the Lower Cretaceous Mannville Group in the Cold Lake study area showing the complex relations of aquifers, oil sand deposits, and shale aquitards.

noticeable on the salinity map for the flow to the south. The overall range of hydraulic heads is large, between 370 m and 530 m. One cannot see clearly the nature of the flow regime in the Mannville aquifer (figure 42c). In the western and southwestern margins of the Cold Lake study area, where lateral flow is noticeable in this aquifer, it is not topographically controlled, even in a subdued way. It is, in fact, of the intermediate type, like the dominantly westward flow in the Clearwater and McMurray aquifers.

There are 4436 bottomhole temperature values in the Mannville aquifer, varying between 12°C at 275 m and 40°C at 1025 m. The temperature distribution shows a general decrease updip (figure 42d), with some variations around 25°C in the large band between the southwest and northeast corners of the study area. This pattern is probably caused by thermal conductivity variations due to the existence of oil sand and heavy oil deposits.

Joli Fou aquitard

The thickness of this shaley aquitard ranges from 2 to 160 m with an average of 26 m, especially W4M. It covers the entire study area, but as the Viking sandstone becomes progressively thinner to the east and northeast the Joli Fou aquitard becomes hydraulically merged with the Colorado aquitard system. Based on published results for the Western Canada Sedimentary Basin, the vertical hydraulic conductivity of the Joli Fou aquitard is estimated at 4×10^{-9} m/d (Basin Analysis Group 1985) with low leaky properties.

Viking aquifer

For the purposes of this study the Viking aquifer comprises the aggregate of the several thin sandstones which are present in the Viking Formation in the Cold Lake study area. It has an average thickness of less than 10 m in the study area and thins considerably in the vicinity of St. Paul (Tp 58 R 9 W4M). Studies of the potentiometric surface of the Viking aquifer in the Western Canada Sedimentary Basin (Hill et al. 1961; Hitchon 1969b, fig. 4) indicate the presence, in central Alberta, of a large closed potentiometric surface low, which is elongated in a general northwest direction, roughly parallel to the axis of the Alberta Basin, and centered at Gilby over the southern end of the Rimbey-Meadowbrook carbonate reef chain. It has been speculated (Hitchon 1969b) that this closed poten-

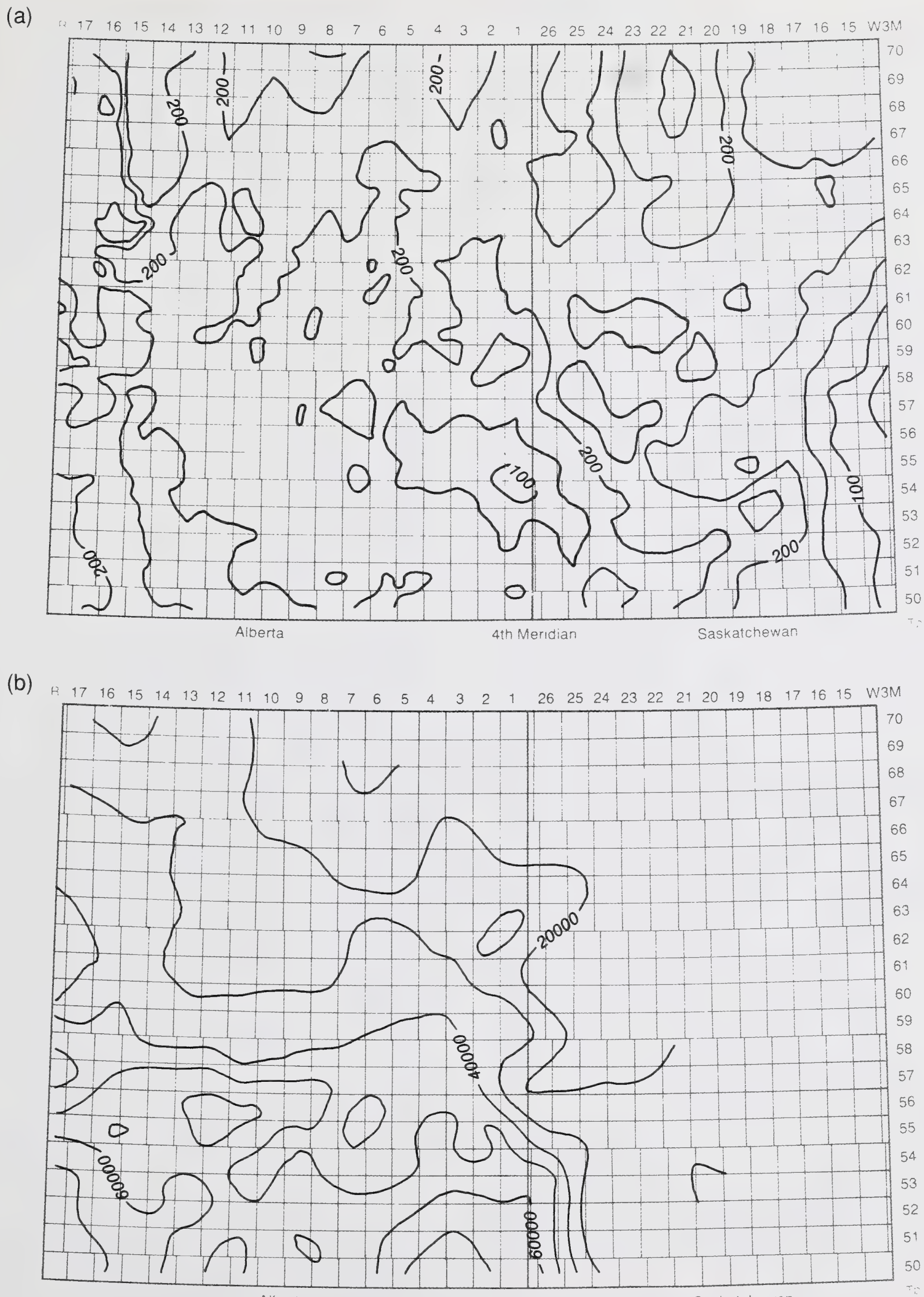


Figure 42. Mannville aquifer hydrogeology. (a) Isopachs (contour interval 50 m); (b) Salinity (mg/L) of formation waters; (c) Potentiometric surface; (d) Temperature distribution (5°C isotherms).

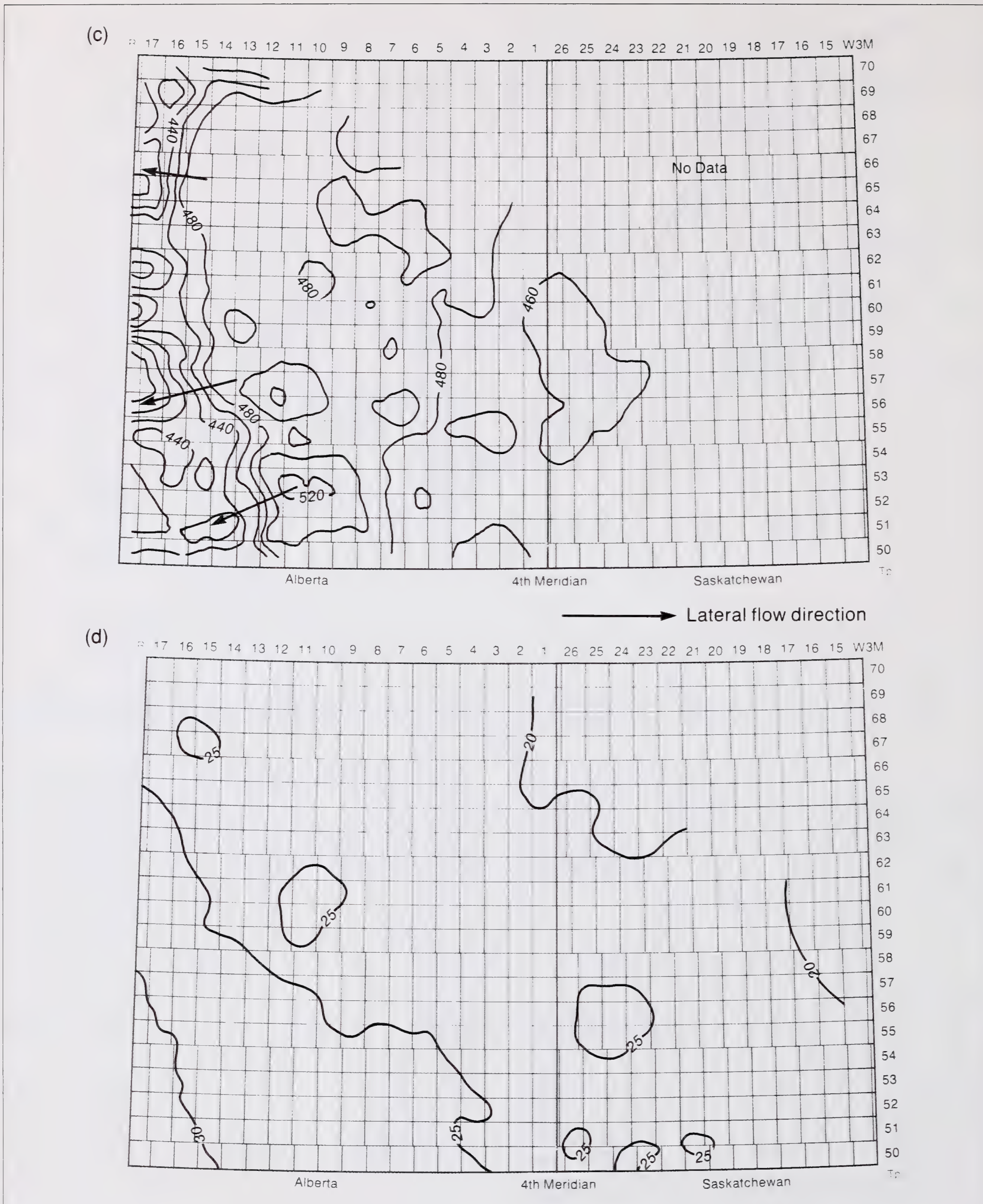


Figure 42. (continued)

tiometric surface low is due to osmotic effects across shale membranes, which are imposed on the gravity flow regime. In the Cold Lake study area, flow directions might, therefore, represent a complex combination of downdip flow toward the closed potentiometric surface low and regional updip flow and topographical influence as observed in local flow regimes.

In the Western Canada Sedimentary Basin the patterns of regional variations in formation water composition appear to relate more to the total thickness of sandstones in the Viking Formation (see Rudkin 1964) than they do to the basinwide variations in the potentiometric surface. This can be seen in maps of the regional distribution of Cl (Hitchon 1964, fig. 15-36) and I (Hitchon et al. 1977, fig. 5). In addition to these factors (1) the Viking aquifer is absent in the northeast part of the study area as well as parts of the eastern and southern boundaries; (2) the individual sandstones are very thin; and (3) the Viking aquifer is as shallow as 200 m in places. Because a detailed investigation of the lithological variations within the Viking Formation was beyond the limits of the present study, the hydrochemical patterns of formation waters in the Viking aquifer can be interpreted only in general terms.

Salinities in the range 40 000 to 60 000 mg/L generally characterize the southern half of the region; values less than 40 000 mg/L occur along parts of the southern border (figure 43a). In this southern area salinity gradients are relatively steep, compared to the northern half of the study area, which has lower salinities, generally in the range 40 000 to 10 000 mg/L. Throughout the area, however, isolated regions of higher or lower salinity occur within these broad regional trends. Corresponding ranges for other components in the southern half of the study area are Cl (40 000 to 25 000 mg/L), Ca (2000 to 1000 mg/L), and Mg (800 to 500 mg/L). In the northern half of the region the corresponding ranges are Cl (25 000 to 10 000 mg/L), Ca (1000 to less than 250 mg/L) and Mg (500 to less than 100 mg/L). Isoconcentration patterns for HCO_3 and SO_4 are difficult to interpret. Based on the previous basinwide studies of potentiometric surface and hydrochemistry of the Viking aquifer cited above, one might speculate that the observed 'patchy' isoconcentration patterns are related to the location of the Cold Lake study area at a hydraulic divide.

The potentiometric surface of the Viking aquifer (figure 43b) is based on 1171 reliable drillstem tests. The range of hydraulic heads is 440 to 640 m. Although there is some subdued similitude between topography and the potentiometric surface (figures 43b, 47 and 48), the flow in the Viking aquifer is best characterized as being of intermediate to local type.

St. Walburg aquifer

This sandstone aquifer is only present south of Tp 65 and east of R 1 W4M. Its thickness is 10 m or more to the east of R 22 W3M. It ranges in thickness from 3 to 50 m with an average of 15 m. Only two reliable drillstem tests indicate hydraulic heads in the same range as those of the Viking aquifer and, for the purpose of this study, it is sufficient to assume that the flow is similar to that in the Viking aquifer.

Colorado aquitard system

In the Cold Lake study area strata younger than the Viking and St. Walburg sandstones are dominantly argillaceous, and for the purpose of this study have been grouped together as the Colorado aquitard system. This aquitard system ranges in thickness from 60 to 680 m (figure 44) and forms the bedrock beneath Quaternary strata. Formation waters have been recovered from minor porous zones at the base of the Fish Scales Zone, within the Second White Speckled Zone, and from the Lea Park Formation. The Belly River Formation contains shallow sandstone aquifers that are used locally by rural residents as a source of domestic (potable) water supply. These shallow groundwaters have not been evaluated in this study, and are a target for oil and gas drilling at depth in the southwest part of the study area. All the deeper formation waters range in salinity between those in the underlying Viking and St. Walburg sandstones and those in the Quaternary (table 5).

Because shallow drillstem test information is sparse, and certainly not sufficient to produce a potentiometric surface for any aquifer in this dominantly shaley and thick aquitard, it is postulated that whenever sandstone bodies are sufficiently continuous the lateral flow is similar to that of the Viking aquifer. Otherwise, the dominant flow is vertically driven by the always positive difference of heads between the Quaternary system and theMannville aquifer.

Only 61 temperature measurements are recorded between the top of the Mannville Group and the top of the bedrock, with values ranging from 15°C at 133 m depth in the northeast of the study area to 34°C at 770 m depth in the southwest. Because these values were measured at different depths in the thick Colorado aquitard system, contouring could not be performed. Another ten temperature values were measured right at the top of the bedrock, at depths varying between 125 m and 270 m, with a distribution precluding meaningful analysis.

Cross-formational flow

This section deals with the regional features of vertical flow between hydrostratigraphic units as they can be derived from point-water hydraulic head cross sec-

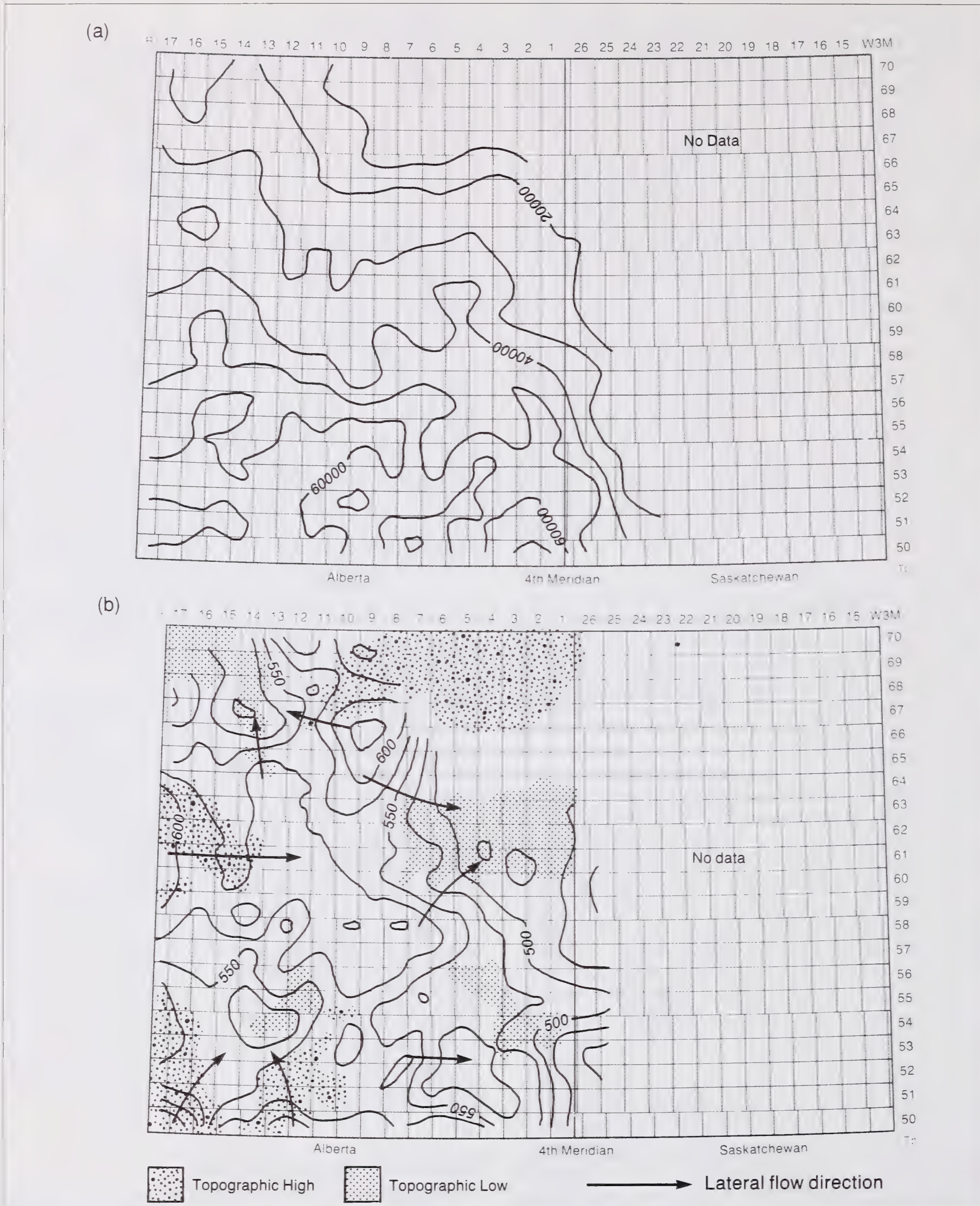


Figure 43. Viking aquifer hydrogeology. (a) Salinity (mg/L) of formation waters; (b) Potentiometric surface.

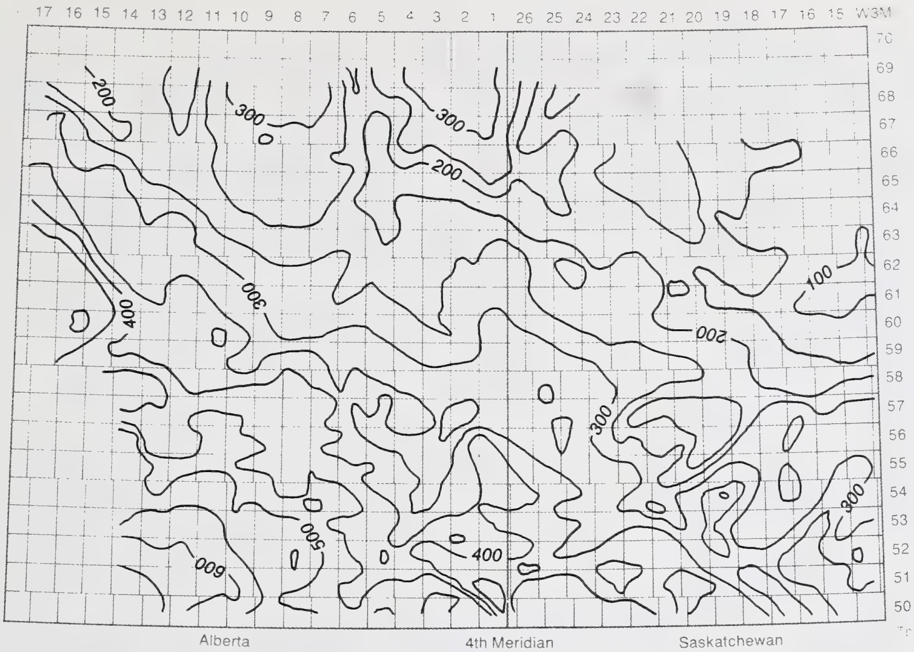


Figure 44. Isopachs of the Colorado aquitard system (contour interval 50 m).

tions; whenever possible, this flow is substantiated by pressure-head vs depth plots.

Vertical flow in the Paleozoic

On the dip cross section in figure 45a, flow is potentially downward from the Beaverhill Lake aquifer system, through the Winnipegosis aquifer system, to the Cambrian aquifer system, except to the northeast of Tp 66 R 2 W4M where there is effective hydraulic continuity between the two lower systems. As illustrated in figure 27, the intervening Lower Devonian aquiclude system becomes thinner in this northeast portion of

Table 5. Chemical composition (mg/L), physical properties and production data for selected formation waters from aquifers in the Colorado aquitard.

Stratigraphic Unit	Base of Fish Scales	Base of Fish Scales	Lea Park Formation	Belly River Formation	Belly River Formation
Location	6-15-53-9-W4M	10-9-55-1-W4M	7-4-50-17-W4M	10-28-52-17-W4M	10-22-51-11-W4M
Depth (m)	548.6-551.6	304-8-309.4	301.8-320.0	215.0-241.0	179.8-207.3
Source	Perforations	DST 6	DST 1	DST 2	DST 1
Recovery	-	137 m sw	219.5 m sw	37 m sw	82.3 m sw
Na (diff.)	22 280*	12 004	3 713	5 395**	1 789
Ca	1 800	586	160	374	10
Mg	790	307	32	155	5
Cl	40 000	20 240	5 920	9 170	2313
HCO_3	303	327	288	183	588
SO_4	2	25	23	189	185
TDS (110°C)	67 605	35 180	10 440	15 360	4 930
TDS (ignition)	58 990	32 150	9 400	14 570	4 220
TDS (calc.)	65 176	33 489	10 136	15 466	4 889
pH (laboratory)	7.3	7.8	8.4	7.7	6.4
	(21°C)	(23.9°C)	(24.4°C)	(22°C)	(20.6°C)
Density (15.56°C)	1.049 (21°C)	1.026	1.008	1.011	1.005
Refractive Index (25°C)	1.343	1.3386	1.3347	1.3357	1.3337
Resistivity (ohm m; 25°C)	0.107	0.218	0.676	0.384	1.46

- = not determined; sw = salt water; * Na 22 000 mg/L; K 280 mg/L; ** Na 5 365 mg/L; K 30 mg/L

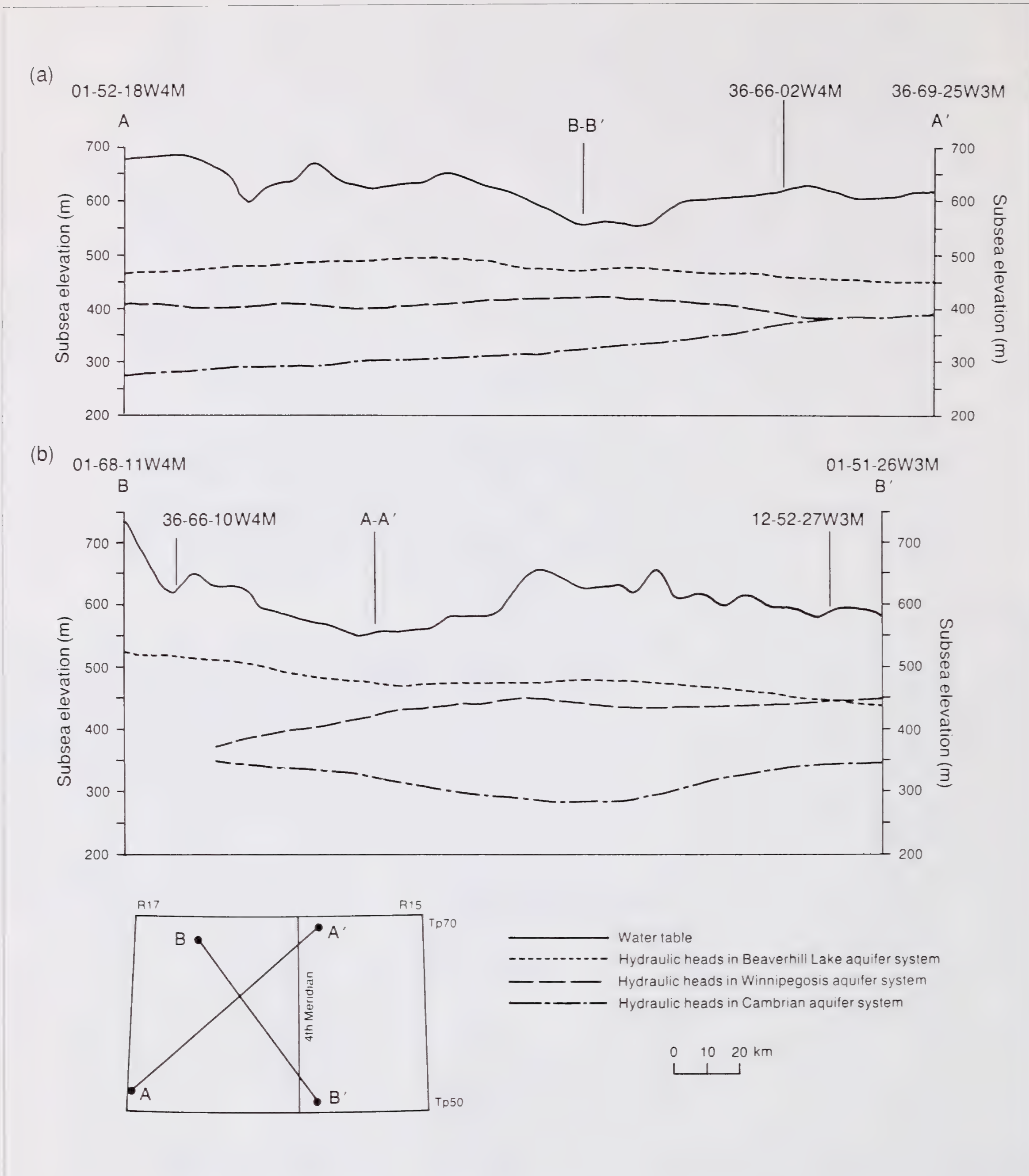


Figure 45. (a) Dip hydraulic head cross section showing possible cross-formational flow between the Paleozoic aquifers; (b) Strike hydraulic head cross section showing potential cross-formational flow between the Paleozoic aquifers.

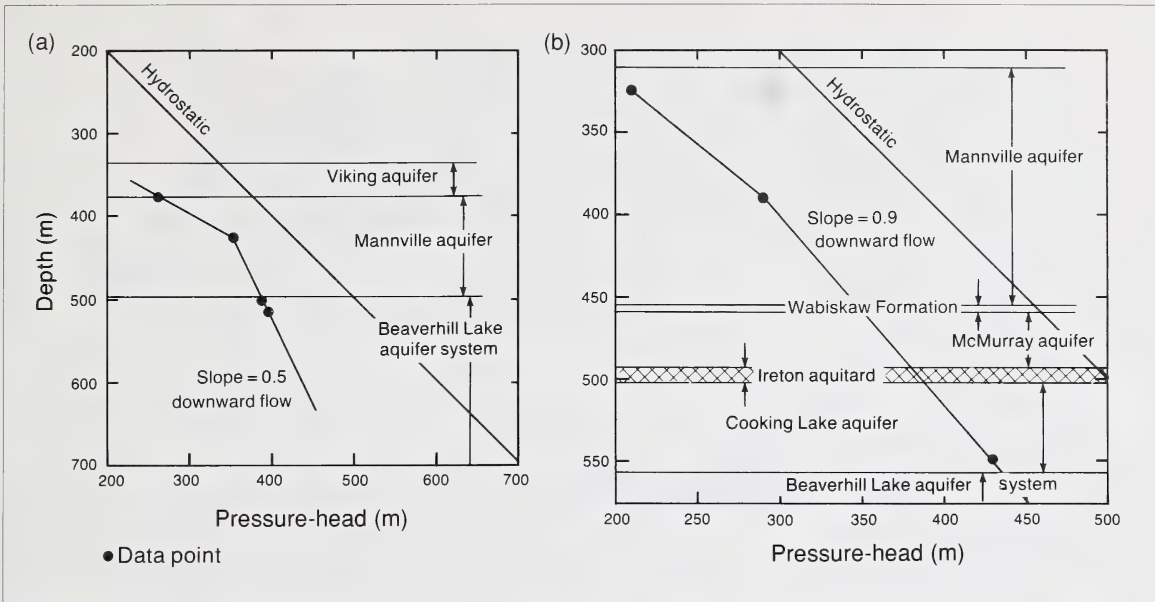


Figure 46. Pressure-head vs depth plots illustrating hydraulic continuity between the Lower Cretaceous and Paleozoic aquifers. (a) At location 06-14-55-02-W4M; (b) At location 10-34-61-08-W4M.

the study area. Before continuity is completely achieved, flow is potentially downward from the Winnipegosis aquifer system to the Cambrian aquifer system through the rapidly decreasing thickness of the intervening aquiclude system. On the stroke cross section in figure 45b, a similar merging of the point-water hydraulic head profiles occurs northwest of Tp 66 R 10 W4M between the Winnipegosis aquifer system and the Cambrian aquifer system, but here the two aquifer systems are separated by about 250 m of the Lower Devonian aquiclude system and the vertical exchange is likely to be minimal. Figure 46 illustrates general downward flow conditions within the Beaverhill Lake aquifer system.

Vertical flow between Paleozoic and Lower Cretaceous

Figure 47a suggests the presence in the southwest part of the Cold Lake study area of a potential upward flow between the Beaverhill Lake aquifer system and the Camrose aquifer through the Ireton aquitard. Beyond the eastern limit of this aquitard the hydraulic heads of the McMurray aquifer and the Beaverhill Lake aquifer system are effectively the same, indicating vertical continuity. Figure 47b shows the same feature of vertical hydraulic continuity for the southeast (south of Tp 60 R 5 W4M) where the Ireton aquitard is very thin or absent. In the northwest, flow is potentially downward from the McMurray aquifer to the Grosmont aquifer. Figure 47c is a NNE-SSW cross section in the western part of the Cold Lake study area; it shows good potential continuity between the Camrose Tongue and McMurray aquifers in the southwest. The flow is potentially upward from the Beaverhill Lake aquifer system to the Grosmont, McMurray, and Clearwater aquifers.

These basic features of the vertical flow conditions between the Paleozoic and the Lower Cretaceous are also present on the east-west cross sections of figure 48. Figure 48a shows that the potentially upward flow from the Beaverhill Lake aquifer system to the McMurray and Mannville aquifers becomes virtual hydraulic continuity east of Tp 64 R 6 W4M. Complete continuity, however, is only observed about 70 km farther to the east (east of Tp 63 R 23 W3M).

On figure 48b, virtual hydraulic continuity of the Beaverhill Lake aquifer system with the McMurray aquifer is already present at Tp 60 R 7 W4M but complete continuity is only established about 50 km to the east (Tp 60 R 3 W4M). Also, in the west-central part of the study area, the vertical flow is potentially upward from the Camrose Tongue aquifer to the McMurray aquifer. Farther south (figure 48c) there is virtually no positive hydraulic head difference between the Camrose Tongue aquifer and the McMurray aquifer. The hydraulic head profile of the Beaverhill Lake aquifer system and that of the Mannville aquifer are very close over most of the cross section.

Vertical flow within the Cretaceous

As illustrated on figures 47 and 48, vertical flow is essentially downward from the Viking aquifer to the Mannville aquifer (with a good separation suggesting a "strong" Joli Fou aquitard) and downward again from

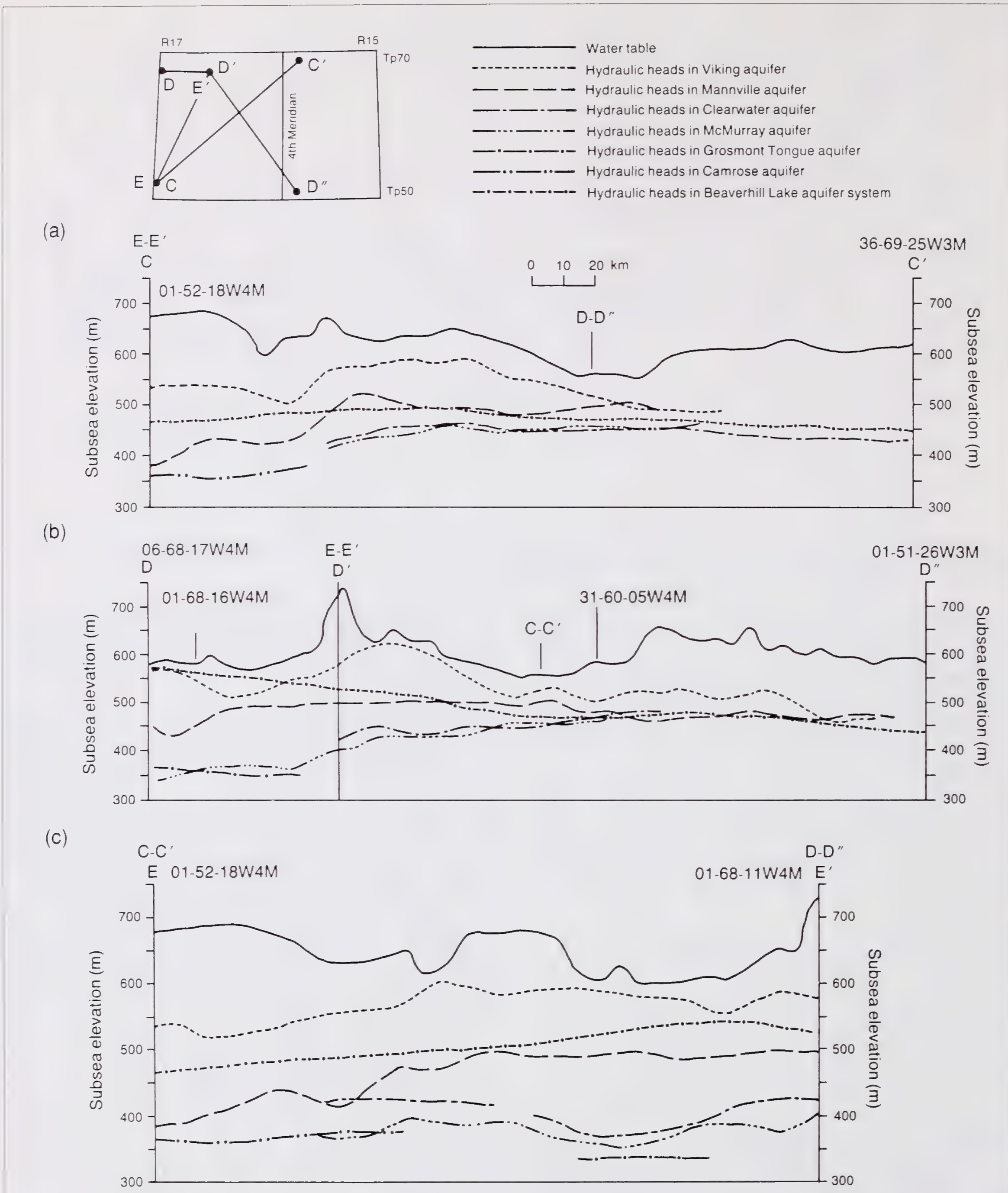


Figure 47. General hydraulic head cross sections showing possible cross-formational flow between the aquifers located above the Prairie aquiclude. (a) Dip; (b) Strike; (c) Northeast-southwest in the western part of the study area.

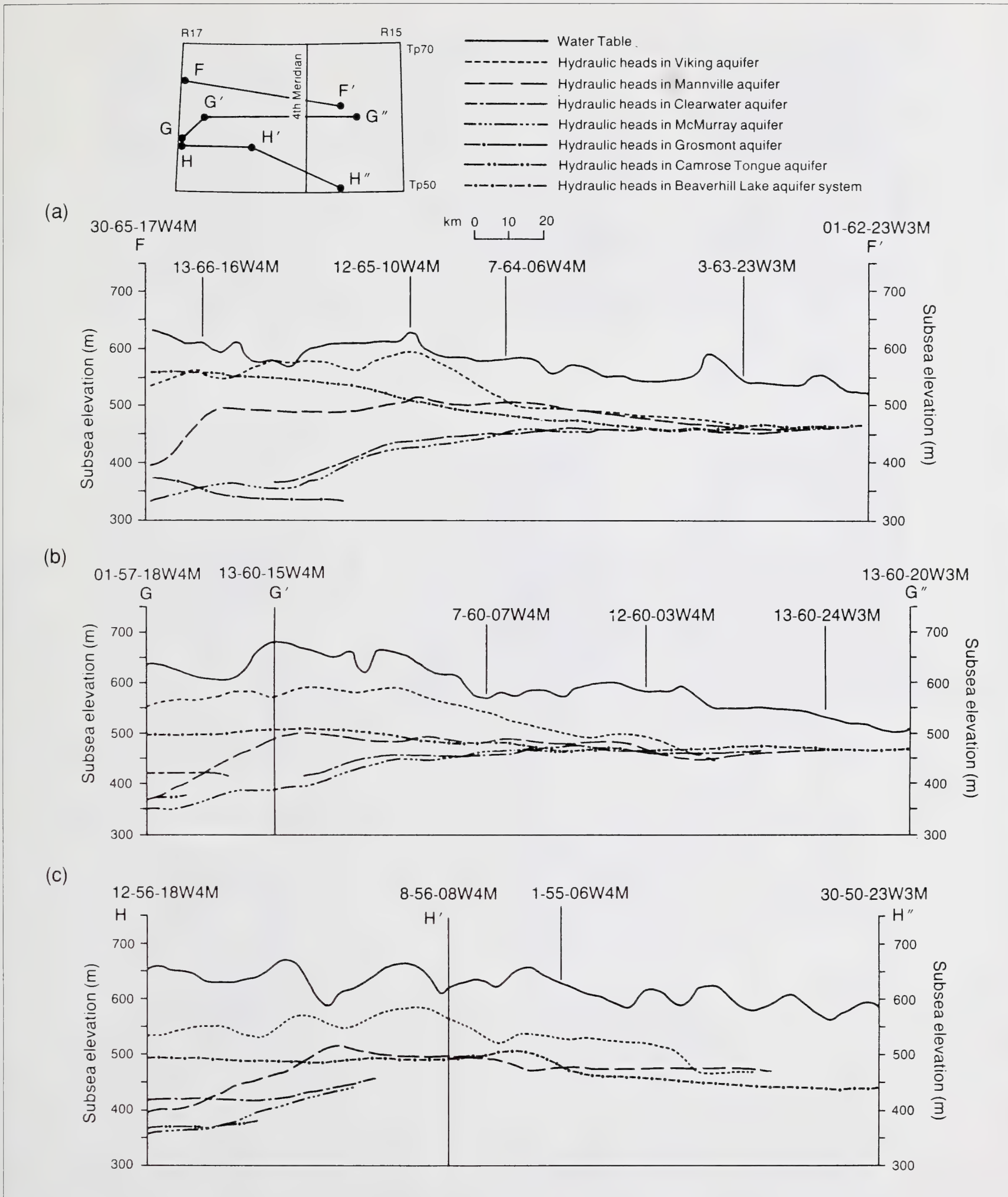


Figure 48. General east-west hydraulic head cross sections.

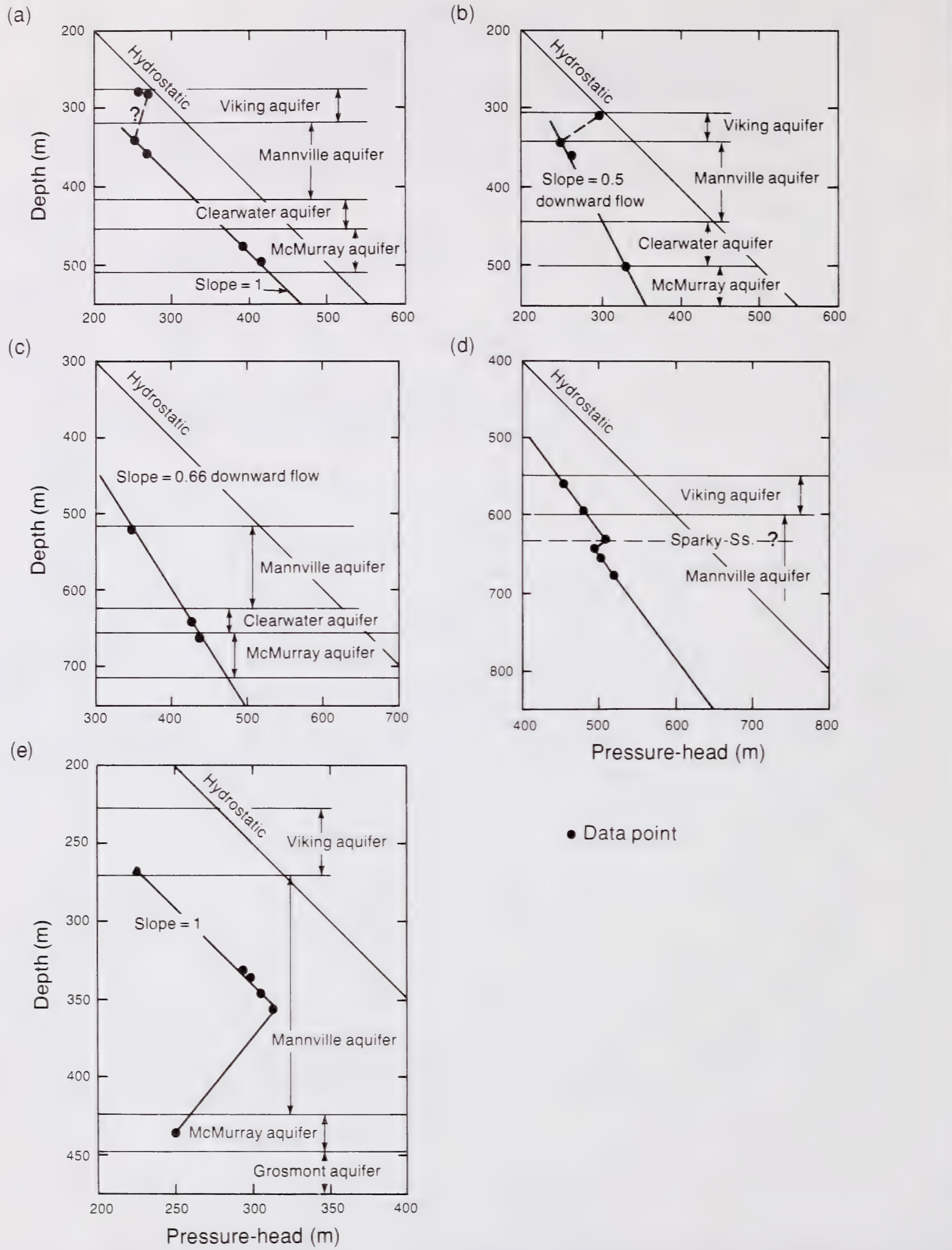


Figure 49. Pressure-head vs depth plots illustrating cross-formational flow between the Lower Cretaceous aquifers. (a) At well location 10-20-60-07-W4M; (b) At well location 01-31-64-08-W4M; (c) At well location 10-36-56-10-W4M; (d) At well location 10-12-53-12-W4M; (e) At well location 11-10-67-14-W4M.

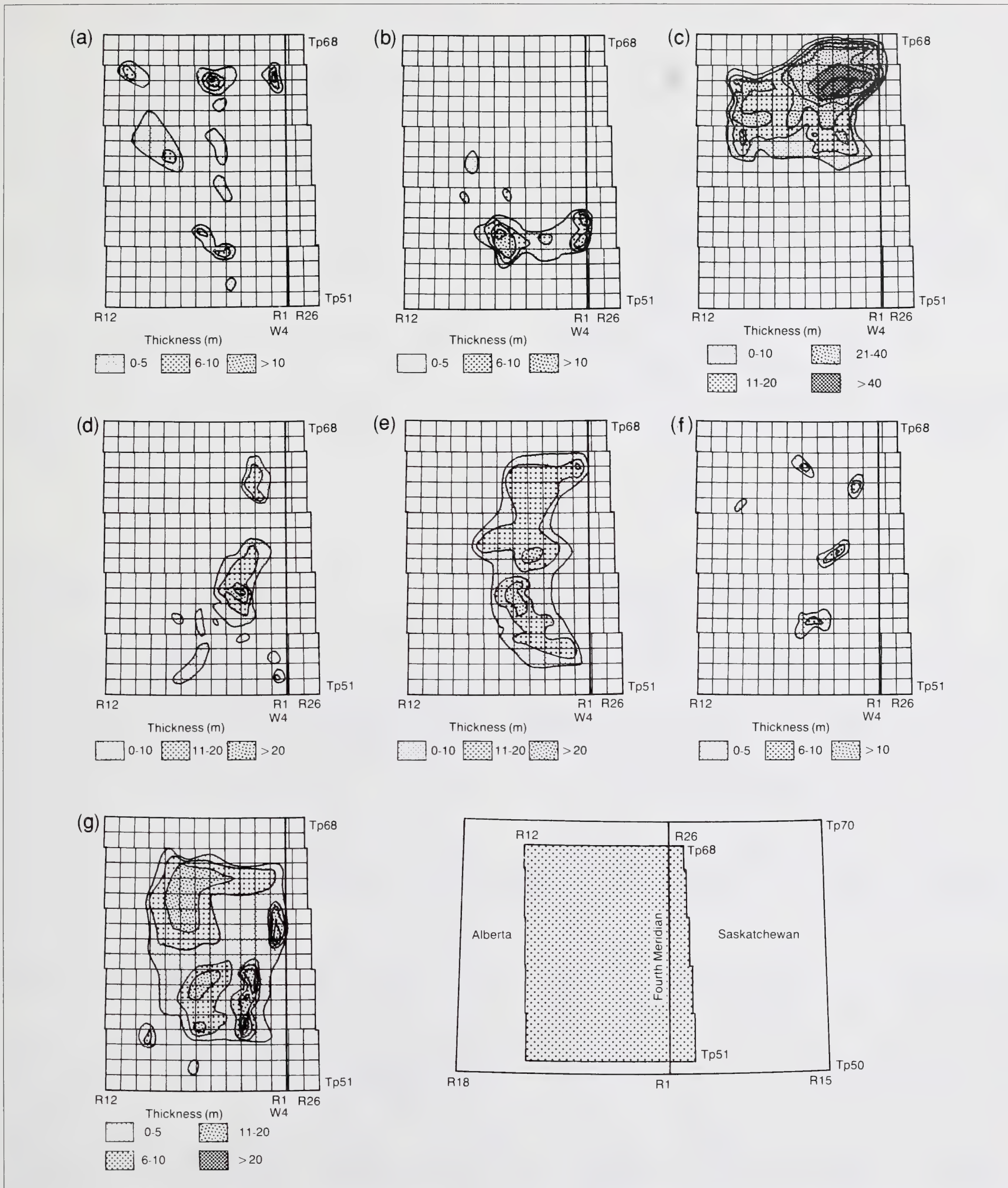


Figure 50. Isopachs of oil sand deposits. (a) McMurray Formation, layer 1; (b) McMurray Formation, layer 2; (c) Clearwater Formation; (d) Lower Grand Rapids Formation, layer 2; (e) Lower Grand Rapids Formation, layer 1; (f) Upper Grand Rapids Formation, layer 2; (g) Upper Grand Rapids Formation, layer 1.

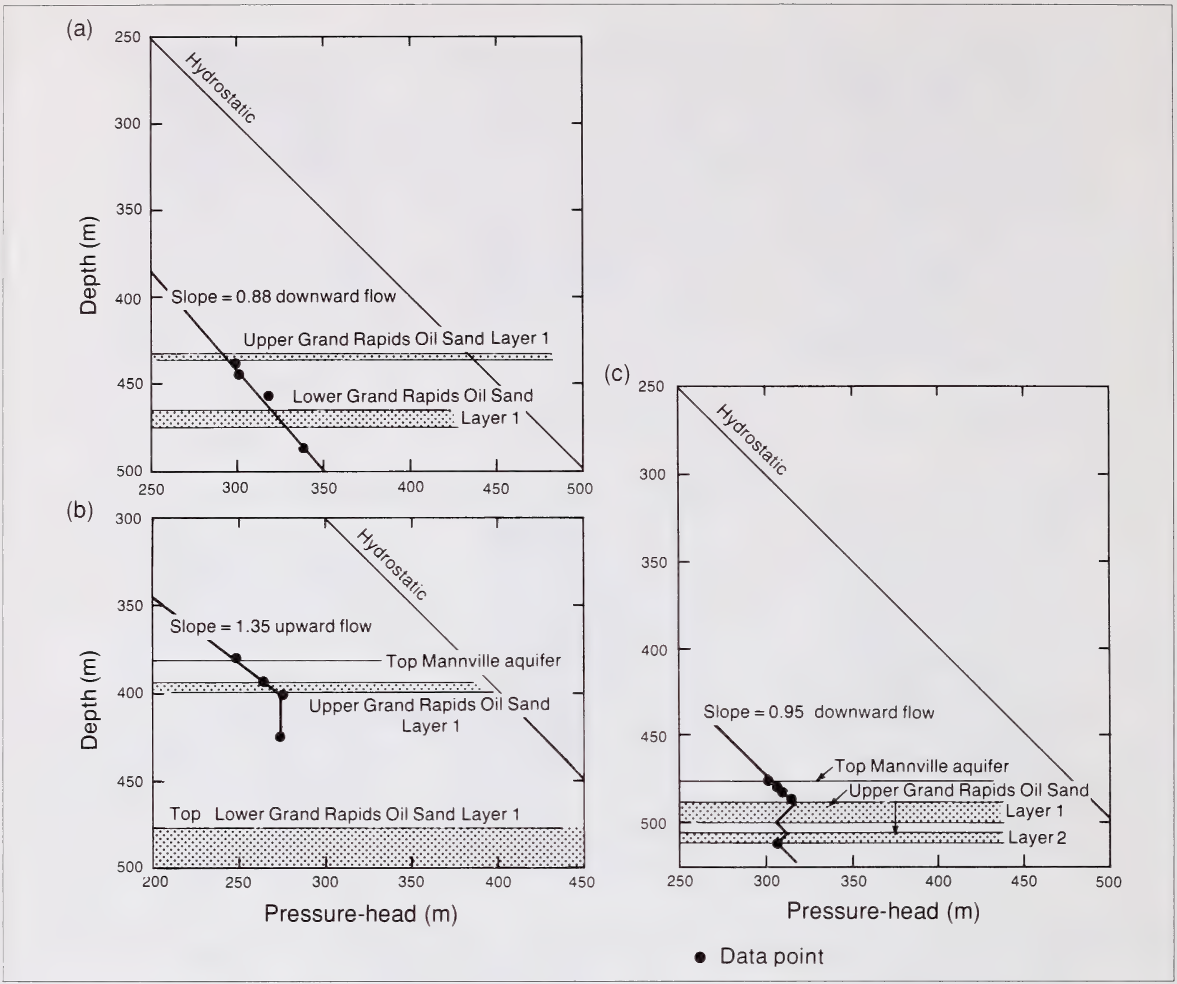


Figure 51. Pressure-head vs depth plots illustrating cross-formational flow in the Mannville Group within the area of the oil sands deposits (Tp 53-66 R 1-11 W4M). (a) At well location 11-36-54-07-W4M; (b) At well location 11-35-55-06-W4M; (c) At well location 11-21-60-08-W4M.

the Mannville aquifer to the Clearwater and McMurray aquifers which are hardly separated. Features that were not apparent in the potentiometric surface map of the Mannville aquifer show that the flow in this aquifer would be best defined as "transitional" between the intermediate flow regime of the Clearwater and McMurray aquifers and the local flow regime of the Viking aquifer.

The vertical flow within the Cretaceous aquifers is illustrated by the plots on figure 49; the conditions are hydrostatic on figure 49a between the Mannville and the McMurray aquifers. Flow is downward at the location of figure 49b and 49c and on both figures the deflections between the Viking and Mannville aquifers are marked. Figures 49d and 49e suggest, on the contrary, that the conditions are quasi-hydrostatic between these two aquifers and that the break occurs farther down at the level of the Clearwater Formation; note that these two plots are both located in the western part of the study area.

Figure 50 shows the distribution of the seven oil sand layers in the Cold Lake Oil Sand Deposit, numbered sequentially downhole. McMurray Formation layer 1 (figure 50a) is also known as the Dina Member and has a rather spotty distribution. McMurray Formation layer 2 (figure 50b) occurs as sand trapped against topographic highs on the pre-Cretaceous erosion surface; it is also known as the Cummings Member and has an average thickness of less than 15 m. The oil sand in the Clearwater Formation (figure 50c) is confined to the northern half of the Cold Lake Oil Sand Deposit and contains most of the bitumen; the sands are continuous, homogeneous, and attain a thickness greater than 40 m. Oil sands in

the lower Grand Rapids Formation comprise two distinct layers; layer 1 averages 15 m thick (figure 50e) and layer 2 less than 10 m thick with a rather spotty distribution (figure 50d). The upper Grand Rapids Formation also contains two oil sand layers, the lower being thin and discontinuous (figure 50f), and the upper layer widespread, generally thin, but ranging in thickness up to more than 20 m in places (figure 50g).

In an attempt to elucidate the vertical flow conditions in the aquifers of the Mannville Group, the data of pressure heads have been allocated to the 20 possible layers that exist in the oil sand area (Tp 53-66 R 1-11 W4M) between the top of the Mannville and the pre-Cretaceous unconformity. No data were found to belong to the Clearwater oil sand and intermediate aquifers and only very few in the McMurray oil sand and intermediate aquifers. Thus, most of the data considered are within the upper portion of the sequence (upper and lower Grand Rapids oil sands and intermediate aquifers). The data indicate a general downward flow trend, with no major aquitard break caused by the oil sand layers. This is interpreted as flow in a single aquifer system and implies at least lateral bypasses of the oil sand layers which act as aquitards. The hydraulic conductivity of the oil sand layers is about 9×10^{-6} m/d (Agar 1985). The "strength" of these aquitards is illustrated by the local pressure-head vs depth plots of figure 51a (no deflections), and 51b and 51c (positive deflections).

From this preliminary analysis of the Mannville aquifer, two partial conclusions can be drawn: (1) the oil sand layers may act as intermediate to weak aquitards; (2) the overall flow in the Mannville aquifer probably laterally bypasses these aquitards and thus they cannot be regarded as sufficiently strong confining layers for deep well injection.

The vertical flow in the Colorado aquitard system is mostly downward as attested by a few values of hydraulic head determined for various aquifers within it.

Conclusions

Fluid flow regime

The regional analysis of the natural fluid flow regime in the sedimentary rocks of the Cold Lake study area has used all available information for the Paleozoic units and selected information only for Cretaceous strata. The hydrostratigraphic units have been grouped into aquifer (and aquitard) systems based on prevailing flow and hydrochemical patterns; these systems are expected to respond to injection stress in a homogeneous fashion. For this refined definition of the hydrostratigraphy, recommended hydraulic parameters are presented in table 6. The values in this table have been selected using a qualitative judgment about the regional representativeness of the core plug and drillstem test results based on the tables of the Appendix; preference has been given to drillstem test results whenever possible (see discussion in Bachu et al. 1987). For hydraulic conductivity, the low and high values are based on the harmonic and arithmetic regional averages of the point values, respectively, while the representative estimates are from the geometric regional averages. For specific storage, the low and high values are from the minimum and maximum values, respectively, of porosity obtained from the core plug determinations; the representative estimates are based on the arithmetic average of the point values. Regional values of vertical anisotropy presented in table 6 indicate quasi-isotropic conditions in the carbonate aquifers and a range between 80 to 200 for the sandstone aquifers.

Lateral flow is dominantly regional and to the northeast in most of the Paleozoic aquifer systems with

Table 6. Regional estimates of hydraulic parameters for selected aquifer systems.

	Horizontal hydraulic conductivity K_h(m/d)			Anisotropy	Specific storage $S_s(m^{-1})$		
Aquifer (system)	Low	Representative	High	K_h/K_v	Low	Representative	High
Post-Viking	-	-	-	-	3.0×10^{-3}	4.7×10^{-3}	6.9×10^{-3}
Viking	2.0×10^{-4}	3.5×10^{-2}	1.300	-	3.0×10^{-4}	4.0×10^{-3}	6.8×10^{-3}
Mannville	1.3×10^{-4}	3.5×10^{-2}	2.400	90.0	1.1×10^{-3}	5.0×10^{-3}	8.5×10^{-3}
Clearwater	3.8×10^{-4}	3.7×10^{-2}	4.200	200.0	1.4×10^{-4}	8.0×10^{-4}	1.1×10^{-3}
McMurray	9.2×10^{-4}	2.7×10^{-2}	9.900	120.0	3.6×10^{-4}	8.0×10^{-3}	1.2×10^{-2}
Grosmont	1.2×10^{-3}	1.7×10^{-2}	8.300	10.0	9.5×10^{-5}	5.5×10^{-4}	1.4×10^{-3}
Camrose Tongue	3.4×10^{-3}	2.2×10^{-2}	2.100	40.0	1.0×10^{-4}	4.4×10^{-4}	8.9×10^{-4}
Beaverhill Lake	6.0×10^{-5}	3.0×10^{-3}	0.077	0.5	1.2×10^{-5}	4.0×10^{-4}	1.5×10^{-3}
Winnipegosis	6.3×10^{-5}	1.1×10^{-2}	0.210	0.8	1.9×10^{-5}	6.5×10^{-4}	6.0×10^{-3}
Basal Red Beds	5.0×10^{-4}	1.1×10^{-2}	0.038	110.0	1.2×10^{-5}	2.0×10^{-4}	4.4×10^{-4}
Cambrian	2.0×10^{-3}	4.3×10^{-2}	0.170	80.0	1.7×10^{-5}	2.8×10^{-4}	5.3×10^{-4}

minor eastward and northwestward components caused by specific boundary conditions. Lateral flow in the McMurray and Clearwater aquifers is of intermediate type and to the west and northwest under the influence of a drain effect by the underlying Grosmont aquifer. Flow in the Mannville aquifer is indeterminate, being between intermediate and local. Lateral flow in the Viking aquifer is of local type.

The trend of vertical flow is normally downward between the Beaverhill Lake and Lower Paleozoic aquifer systems. Hydraulic continuity may exist between the three Paleozoic aquifer systems (Beaverhill Lake, Winnipegosis, and Lower Paleozoic) for a critical area to the east of the Cold Lake study area where intervening aquicludes are absent; in fact, upward hydraulic connection is possible up to the top of the Mannville aquifer in this critical area. In the west of the study area hydraulic continuity is practically established between the McMurray and Clearwater aquifers and the Grosmont aquifer. In the east of the study area, where the Ireton aquitard is either thin or missing, there is hydraulic continuity between the Beaverhill Lake aquifer system and the overlying Mannville aquifer. Elsewhere, flow is potentially upward from the Beaverhill Lake aquifer system through the Ireton aquitard. The Joli Fou aquitard that separates the Viking aquifer from the Mannville aquifer represents a strong separation for the flow between these units; flow is potentially downward through this aquitard. The oil sand deposits and the Clearwater shales are weak aquitards; the oil sand deposits are bypassed by flow within the Mannville aquifer. Vertical flow in the Colorado aquitard system is essentially downward.

Geothermal regime

Temperature distributions in each hydrostratigraphic unit show a strong correlation with the stratigraphic dip (general temperature decrease updip from southwest to northeast), which points again to a strong conductive regime. This is also the direction of the flow of formation waters in the regional system. If the fluid flow had been strong enough to convect heat significantly, then the temperatures would be higher downstream, toward the discharge areas in the northeast. Temperatures vary between 12°C and 70°C for depths ranging from 125 m at the top of the bedrock to 1997 m at the top of the Precambrian basement in the southwest corner of the study area.

Although there are a great many bottomhole temperature measurements in the study area they are unevenly distributed, both areally and with depth, such that it is very difficult to define individual geothermal gradients characterizing the stratigraphic or hydrostratigraphic units. However, the heat flow in the Cold Lake study area can be characterized by the distribution of the integral geothermal gradient $\overline{G}$, which is defined (Bachu 1988) as the weighted average of the individual geothermal gradients over the sedimentary column above the Precambrian basement:

$$\overline{G} = (T_b - T_o)/Z \equiv Q/\overline{\lambda} \qquad (8)$$

where T_b and T_o are the temperatures at the bottom and top of the sedimentary column, Z is the thickness of the sediments, Q is the heat flux and $\overline{\lambda}$ is the average thermal conductivity of the sediments. The integral geothermal gradient is computed as the temperature difference between bottom and top vs the total depth. The temperature of 6°C at the top is given by the mean annual temperature, considering a ground temperature of 0°C whenever air temperatures dip below zero (Environment Canada 1982). Figure 52 presents the distribution of the integral geothermal gradient in the Cold Lake study area. In the absence of convective effects due to the flow of formation waters, and assuming a constant heat flux at the bottom of the sediments (Bachu 1988), the distribution of the integral geothermal gradients is controlled by the geometry and lithology of the strata above the basement (Bachu 1985). Indeed, the distribution of the integral geothermal gradients (figure 52) and of temperatures at the top of the Precambrian (base of Basal Cambrian sandstone) (figure 23) can be explained in terms of stratigraphic and lithological variations in the sedimentary rocks.

For a given constant heat flux at the top of the Precambrian basement, the integral geothermal gradient is dependent on the average thermal conductivity of the rocks. The average thermal conductivity is lowest in the southwest corner of the Cold Lake study area due to the highest proportion of shale in the sedimentary column (up to 200 m of uneroded Ireton Formation present), with a resulting 'high' integral geothermal gradient (up to 30°C/km). The average thermal conductivity increases eastward and northward due to the thinning of the Ireton shales through erosion at the pre-Cretaceous unconformity, resulting in a lower integral geothermal gradient. The effect of the Grosmont Formation carbonates 'replacing' Ireton shales explains the pattern in the northwest corner of the study area. The average thermal conductivity is highest in the west-central part of the Cold Lake study area, due to the absence of Ireton shales (lowest thermal conductivity) and presence of salt (highest thermal conductivity) in the Prairie, Cold Lake, and Lotsberg Formations. As a result, the integral geothermal gradient is lowest in this area (as low as 17°C/km). The geothermal gradient increases again toward the northeast, which can be explained by a decrease in the average thermal conductivity due to salt solution. However, the increase is somehow higher than expected. Because this feature is determined by a single data point, more information is needed to verify and explain this trend. The average thermal conductivity decreases again at the eastern margin and in the southeast corner of the study area

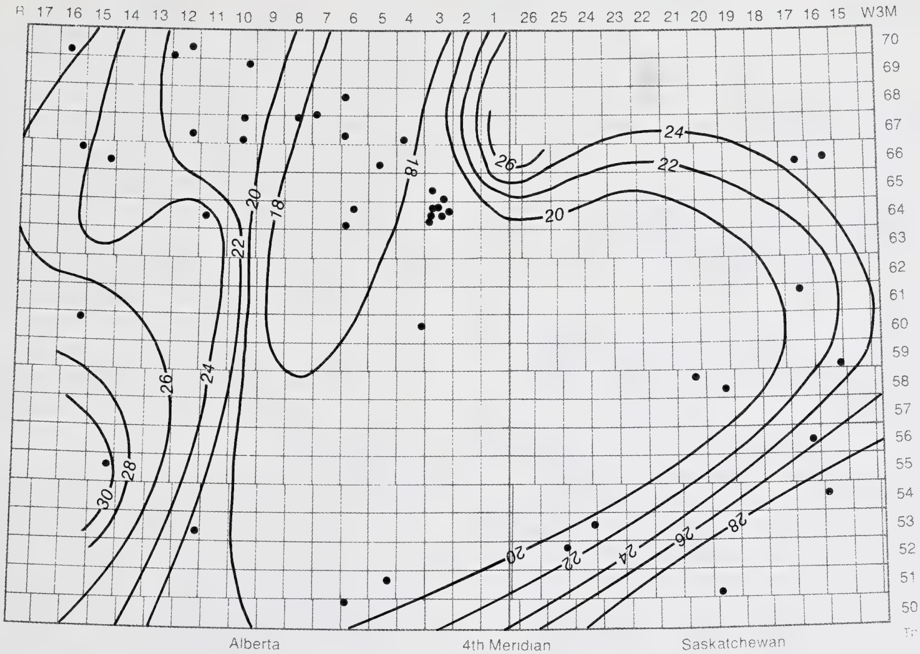


Figure 52. Distribution of the integral geothermal gradient at the top of the Precambrian (base of Basal Cambrian sandstone, contour interval 2°C/km).

due to the absence of halite. As a result, higher integral geothermal gradients are present along the eastern edge and in the southeast corner of the Cold Lake study area (up to 29°C/km). The variations in the average thermal conductivity of the sedimentary column explain also the temperature distribution at the top of the Precambrian (figure 23). Given the fact that the ground relief is relatively flat in the Cold Lake study area, the isotherms at the top of the Precambrian should show the same southwest-northeast regular distribution as the structure contours (figure 3a), if it were not for these changes in thermal conductivity due to lithological changes. The temperature at the bottom of the sedimentary column has to vary according to the variations in thermal conductivity, in order to accommodate the heat flux coming from the bottom and being transferred to the atmosphere at a constant surface temperature. For this reason there is a certain similarity between the distributions of temperatures and integral geothermal gradients at the top of the Precambrian basement (figures 23 and 52, respectively).

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Appendix A. Regional hydrodynamic data

This Appendix presents, in tabular and graphical form, the results of the regional data processing for the hydrodynamic data. The format is by hydrostratigraphic unit from the base to the top of the sedimentary block in the Cold Lake study area. Only the aquifer units for which the data are sufficient have been considered.

Table A1. Hydraulic parameters for hydrostratigraphic units in the Cold Lake area, Alberta, determined from core analyses.

Hydrostratigraphic unit		No. of values	Minimum value	Harmonic average	Geometric average	Median value	Arithmetic average	Maximum value
Cambrian	K_M	200	$3.8x10^{-5}$	$2.0x10^{-3}$	$1.1x10^{-1}$	$2.3x10^{-1}$	1.11	12.8
	K_{90}	37	$8.5x10^{-5}$	$2.0x10^{-3}$	$1.5x10^{-2}$	$1.5x10^{-2}$	$8.4x10^{-2}$	$8.3x10^{-1}$
	K_v	22	$3.1x10^{-4}$	$1.6x10^{-3}$	$5.2x10^{-3}$	$4.7x10^{-3}$	$2.7x10^{-2}$	$3.0x10^{-1}$
	S_s	271	$1.7x10^{-5}$	-	-	$2.7x10^{-4}$	$2.8x10^{-4}$	$5.3x10^{-4}$
Basal Red Beds	K_M	272	$1.7x10^{-5}$	$7.2x10^{-4}$	$8.4x10^{-2}$	$2.1x10^{-1}$	$5.2x10^{-1}$	5.3
	K_{90}	11	$1.5x10^{-4}$	$1.3x10^{-3}$	$1.2x10^{-2}$	-	$4.2x10^{-2}$	$1.3x10^{-1}$
	K_v	8	$3.4x10^{-5}$	$1.7x10^{-4}$	$8.0x10^{-4}$	-	$2.0x10^{-4}$	$4.4x10^{-4}$
	S_s	299	$1.2x10^{-5}$	-	-	$2.0x10^{-4}$	$2.0x10^{-4}$	$4.4x10^{-4}$
Winnipegosis	K_M	77	$1.5x10^{-5}$	$7.0x10^{-5}$	$2.0x10^{-4}$	$1.5x10^{-4}$	$2.2x10^{-2}$	1.42
	K_{90}	55	$1.5x10^{-5}$	$5.0x10^{-5}$	$1.0x10^{-4}$	-	$6.0x10^{-4}$	$1.2x10^{-2}$
	K_v	11	$1.5x10^{-5}$	$7.0x10^{-5}$	$3.0x10^{-4}$	-	$2.7x10^{-2}$	$2.4x10^{-2}$
	S_s	112	1.9x10-5	-	-	$5.6x10^{-4}$	$7.0x10^{-4}$	$6.0x10^{-3}$
Beaverhill Lake	K_M	173	$1.7x10^{-5}$	$7.0x10^{-5}$	$2.0x10^{-4}$	$1.0x10^{-4}$	$2.3x10^{-3}$	$7.9x10^{-2}$
	K_{90}	145	$1.7x10^{-5}$	$5.0x10^{-5}$	$2.0x10^{-4}$	$1.0x10^{-4}$	$2.0x10^{-3}$	$6.6x10^{-2}$
	K_v	57	$1.7x10^{-5}$	$1.7x10^{-4}$	$5.0x10^{-4}$	$4.5x10^{-4}$	$2.0x10^{-3}$	$3.1x10^{-2}$
	S_s	222	$1.2x10^{-5}$	-	-	$4.0x10^{-4}$	-	$1.5x10^{-3}$
Camrose Tongue	K_M	38	$2.9x10^{-4}$	$4.1x10^{-3}$	$1.1x10^{-1}$	$1.1x10^{-1}$	2.06	26.2
	K_{90}	43	$8.8x10^{-5}$	$1.3x10^{-3}$	$4.2x10^{-2}$	$4.6x10^{-2}$	$5.9x10^{-1}$	9.98
	K_v	36	$3.5x10^{-5}$	$3.8x10^{-4}$	$2.9x10^{-3}$	$3.3x10^{-3}$	$3.3x10^{-2}$	$6.6x10^{-1}$
	S_s	44	$1.0x10^{-4}$	-	-	$4.4x10^{-4}$	-	$8.9x10^{-4}$
Grosmont	K_M	434	$2.5x10^{-5}$	$1.2x10^{-3}$	$4.6x10^{-2}$	$5.2x10^{-2}$	$5.5x10^{-1}$	25.1
	K_{90}	393	$1.7x10^{-5}$	$6.2x10^{-4}$	$2.3x10^{-2}$	$2.5x10^{-2}$	$3.9x10^{-1}$	25.1
	K_v	308	$1.7x10^{-5}$	$2.6x10^{-4}$	$5.3x10^{-3}$	$5.4x10^{-3}$	$1.1x10^{-1}$	6.08
	S_s	468	$9.5x10^{-5}$	-	-	$5.0x10^{-4}$	-	$1.4x10^{-3}$
McMurray	K_M	482	$1.1x10^{-4}$	$1.3x10^{-3}$	$4.7x10^{-1}$	$9.1x10^{-1}$	1.89	9.9
	K_{90}	37	$2.4x10^{-4}$	$4.2x10^{-3}$	$2.3x10^{-2}$	$2.5x10^{-2}$	$2.0x10^{-1}$	1.4
	K_v	36	$6.7x10^{-4}$	$7.9x10^{-4}$	$7.4x10^{-3}$	$4.2x10^{-3}$	$2.4x10^{-1}$	1.67
	S_s	1879	$3.6x10^{-4}$	-	-	$8.1x10^{-3}$	$7.7x10^{-3}$	$1.2x10^{-2}$
Clearwater	K_M	2549	$8.4x10^{-5}$	$3.2x10^{-2}$	1.57	1.67	2.79	12.2
	K_{90}	201	$1.7x10^{-5}$	$1.0x10^{-4}$	$2.0x10^{-4}$	$8.3x10^{-4}$	$3.4x10^{-2}$	1.55
	K_v	261	$1.7x10^{-5}$	$8.0x10^{-5}$	$7.0x10^{-4}$	$8.3x10^{-4}$	$3.4x10^{-1}$	4.79
	S_s	13776	$2.3x10^{-5}$	-	-	$8.2x10^{-4}$	$8.0x10^{-4}$	$1.1x10^{-3}$
Mannville	K_M	8832	$1.7x10^{-5}$	$5.9x10^{-3}$	$3.2x10^{-1}$	$6.3x10^{-1}$	1.23	15.0
	K_{90}	726	$1.7x10^{-5}$	$3.6x10^{-4}$	$9.3x10^{-3}$	$1.7x10^{-2}$	$1.3x10^{-1}$	12.3
	K_v	657	$1.7x10^{-5}$	$2.6x10^{-4}$	$3.9x10^{-3}$	$6.7x10^{-3}$	$5.2x10^{-2}$	1.4
	S_s	28504	$3.0x10^{-3}$	-	-	$4.4x10^{-3}$	$5.5x10^{-3}$	$8.5x10^{-3}$
Viking	K_M	158	$4.2x10^{-5}$	$2.6x10^{-3}$	$2.8x10^{-1}$	$8.4x10^{-1}$	1.3	8.32
	K_{90}	-	-	-	-	-	-	-
	K_v	3	$3.3x10^{-4}$	-	-	-	-	$3.0x10^{-1}$
	S_s	321	$3.1x10^{-3}$	-	-	$4.7x10^{-3}$	$4.4x10^{-3}$	$6.6x10^{-3}$

K_M – maximum horizontal hydraulic conductivity
K_{90} – horizontal hydraulic conductivity at 90° angle with K_M
K_v – vertical hydraulic conductivity
S_s – specific storage
Median – 50% value on the log-normal frequency plot for K and on the normal frequency plot for S_s
Hydraulic conductivity values are given in (m/d), and specific storage values given in (m^{-1})

Appendix A. (continued)

Table A2. Hydraulic parameters for hydrostratigraphic units in the Cold Lake area, Alberta, determined from drillstem tests.

Hydrostratigraphic unit		No. of values	Minimum value	Harmonic average	Geometric average	Median value	Arithmetic average	Maximum value
Winnipegosis	K	27	1.6×10^{-5}	3.0×10^{-4}	1.1×10^{-2}	1.1×10^{-2}	2.1×10^{-1}	3.46
Beaverhill Lake	K	44	1.4×10^{-5}	3.8×10^{-4}	7.3×10^{-3}	7.3×10^{-3}	7.7×10^{-2}	8.6×10^{-1}
Camrose Tongue	K	39	2.9×10^{-4}	3.4×10^{-3}	2.2×10^{-2}	2.2×10^{-2}	1.4×10^{-1}	1.12
Grosmont	K	8	2.0×10^{-4}	1.2×10^{-3}	1.4×10^{-2}	7.3×10^{-2}	9.8×10^{-2}	5.4×10^{-1}
McMurray	K	137	5.6×10^{-5}	9.2×10^{-4}	3.0×10^{-2}	1.0×10^{-2}	1.52	26.7
	S_s	186	2.0×10^{-3}	-	-	-	3.2×10^{-3}	4.3×10^{-3}
Clearwater	K	96	1.8×10^{-5}	3.8×10^{-4}	1.4×10^{-2}	1.0×10^{-2}	1.5×10^{-1}	9.5×10^{-1}
	S_s	118	4.4×10^{-4}	-	-	-	4.5×10^{-4}	4.7×10^{-4}
Mannville	K	1497	9.0×10^{-7}	1.3×10^{-4}	2.3×10^{-3}	1.8×10^{-3}	1.6×10^{-2}	8.6×10^{-1}
	S_s	1615	5.2×10^{-6}	-	-	-	4.5×10^{-4}	4.7×10^{-4}
Viking	K	1167	1.0×10^{-6}	1.9×10^{-4}	2.1×10^{-2}	3.5×10^{-2}	1.14	69.1
	S_s	1226	2.1×10^{-6}	-	-	-	2.3×10^{-3}	3.4×10^{-2}

K – bulk (radial) hydraulic conductivity
S_s – specific storage
Median – 50% value on the log-normal frequency plot for K
Hydraulic conductivity values are given in (m/d), and specific storage values given in (m^{-1})

Appendix A. (continued)

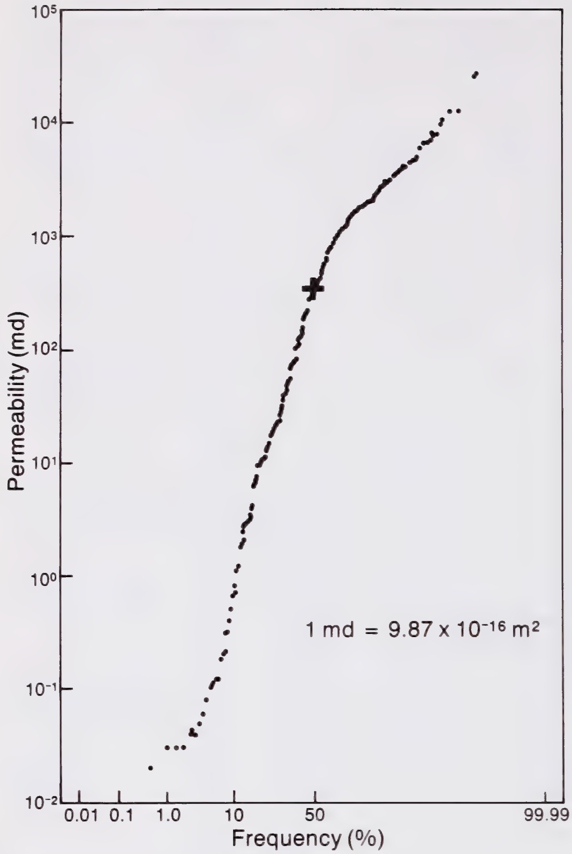

Figure A1. Log-normal cumulative frequency plot for maximum horizontal permeability as derived from core analyses, Basal Cambrian aquifer, Cold Lake study area.

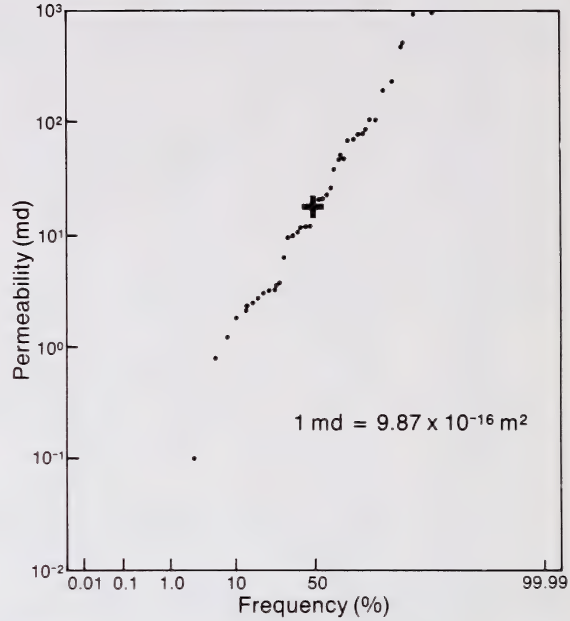

Figure A2. Log-normal cumulative frequency plot for horizontal permeability at 90° with the maximum horizontal as derived from core analyses, Basal Cambrian aquifer, Cold Lake study area.

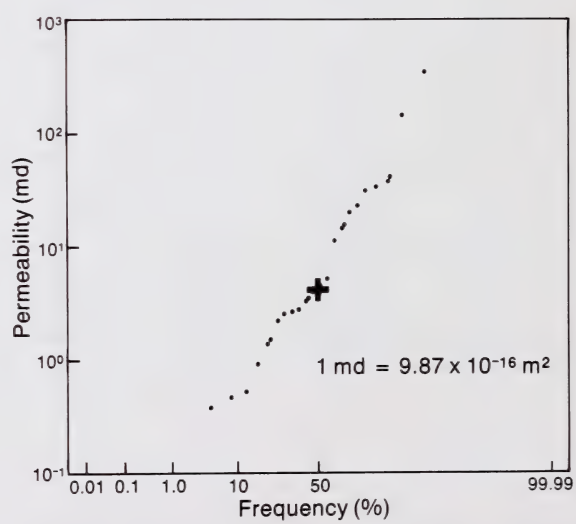

Figure A3. Log-normal cumulative frequency plot for vertical permeability as derived from core analyses, Basal Cambrian aquifer, Cold Lake study area.

Appendix A. (continued)

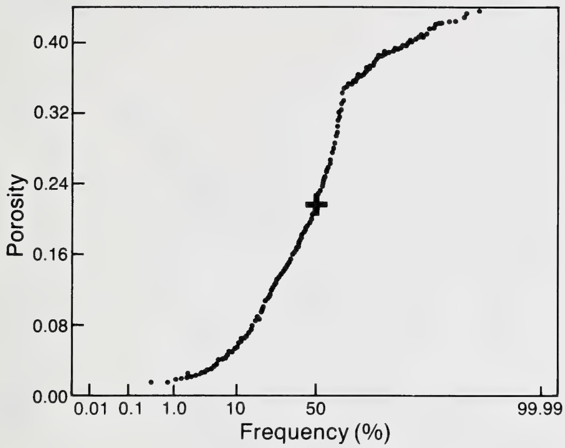

Figure A4. Normal cumulative frequency plot for porosity as derived from core analyses, Basal Cambrian aquifer, Cold Lake study area.

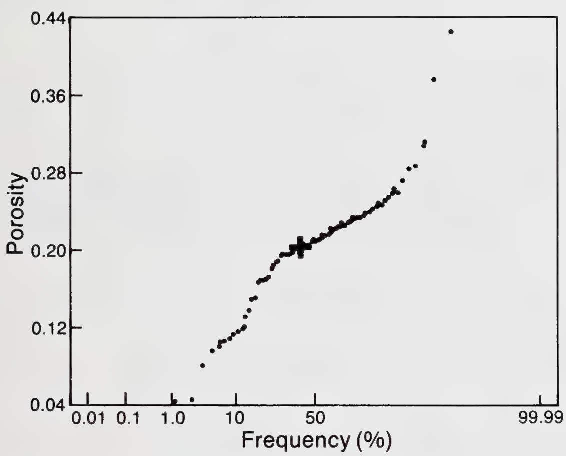

Figure A6. Normal cumulative frequency plot for porosity as derived from core analyses, Cambrian aquifer, Cold Lake study area.

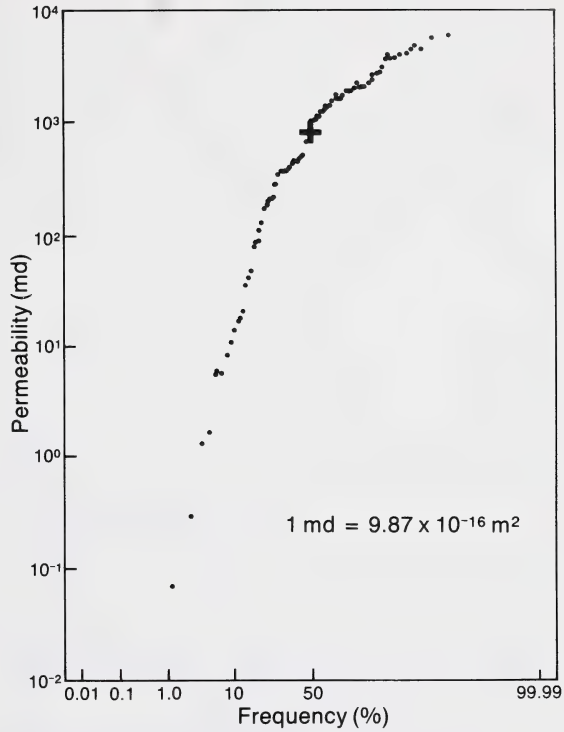

Figure A5. Log-normal cumulative frequency plot for maximum horizontal permeability as derived from core analyses, Cambrian aquifer, Cold Lake study area.

Appendix A. (continued)

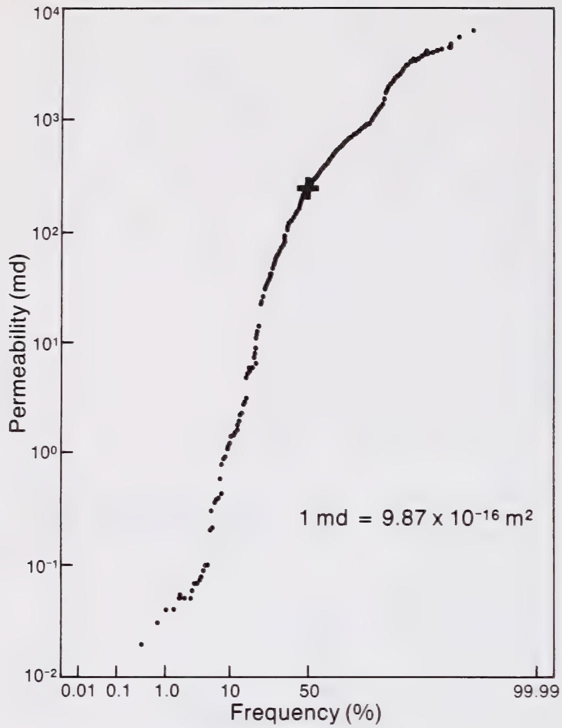

Figure A7. Log-normal cumulative frequency plot for maximum horizontal permeability as derived from core analyses, Basal Red Beds "aquifer", Cold Lake study area.

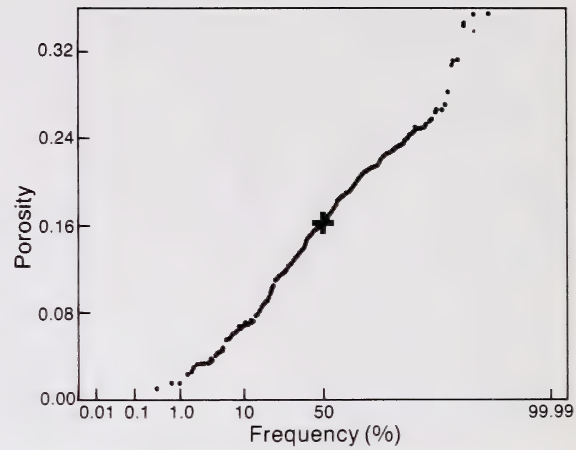

Figure A8. Normal cumulative frequency plot for porosity as derived from core analyses, Basal Red Beds "aquifer", Cold Lake study area.

Appendix A. (continued)

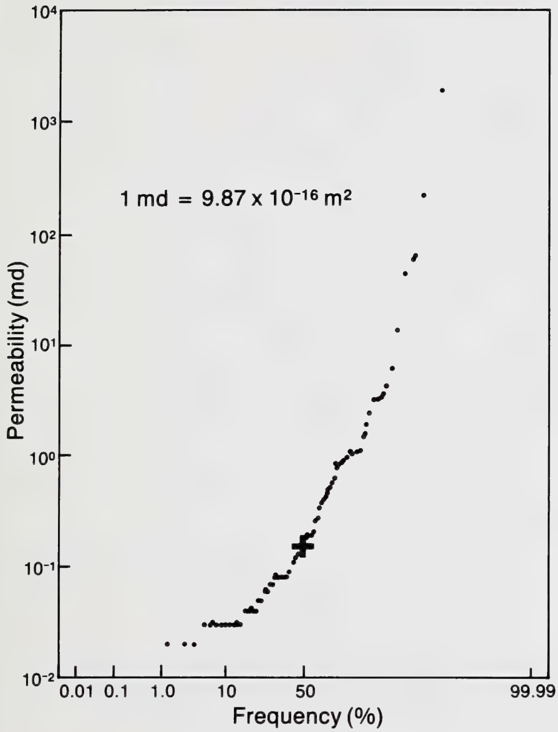

Figure A9. Log-normal cumulative frequency plot for maximum horizontal permeability as derived from core analyses, Winnipegosis aquifer, Cold Lake study area.

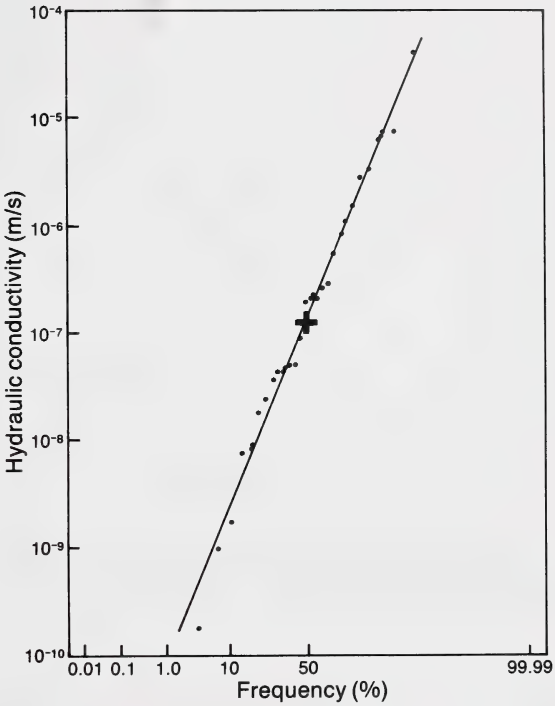

Figure A10. Log-normal cumulative frequency plot for hydraulic conductivity as derived from drillstem tests, Winnipegosis aquifer system, Cold Lake study area.

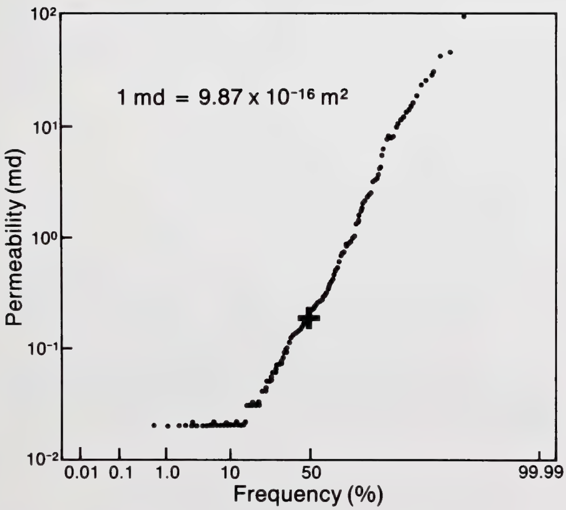

Figure A11. Log-normal cumulative frequency plot for maximum horizontal permeability as derived from core analyses, Beaverhill Lake aquifer, Cold Lake study area.

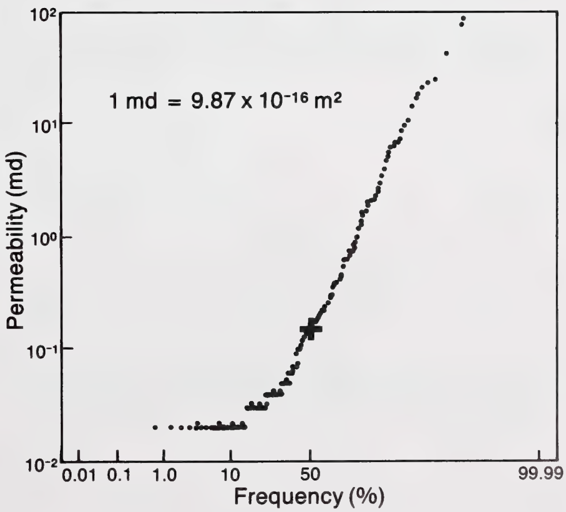

Figure A12. Log-normal cumulative frequency plot for horizontal permeability at 90° with the maximum horizontal as derived from core analyses, Beaverhill Lake aquifer, Cold Lake study area.

Appendix A. (continued)

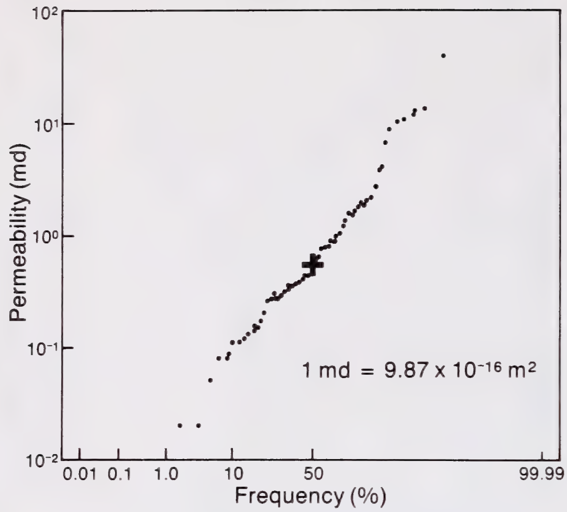

Figure A13. Log-normal cumulative frequency plot for vertical permeability as derived from core analyses, Beaverhill Lake aquifer, Cold Lake study area.

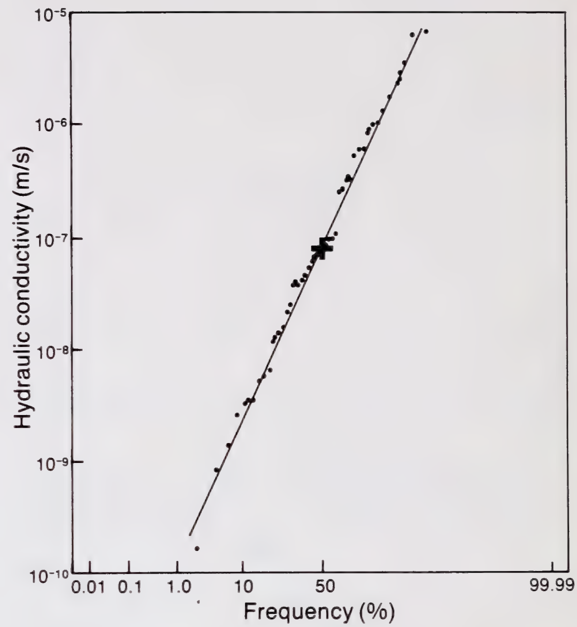

Figure A14. Log-normal cumulative frequency plot for hydraulic conductivity as derived from drillstem tests, Beaverhill Lake aquifer system, Cold Lake study area.

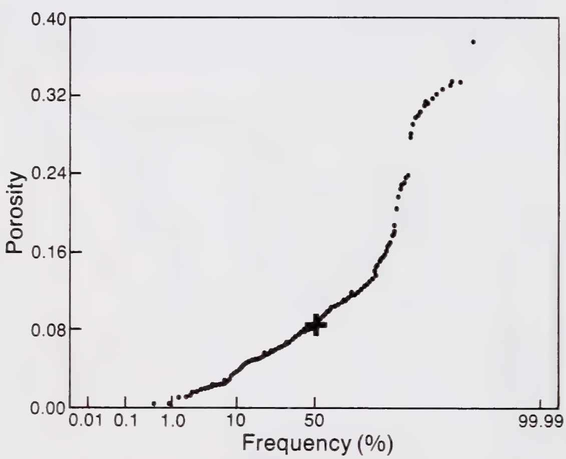

Figure A15. Normal cumulative frequency plot for porosity as derived from core analyses, Beaverhill Lake aquifer, Cold Lake study area.

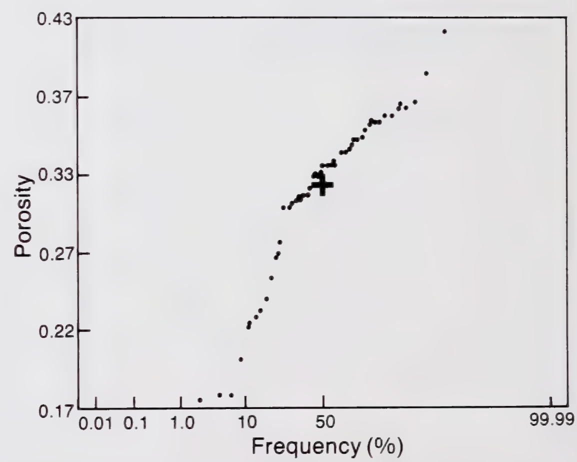

Figure A16. Normal cumulative frequency plot for porosity as derived from core analyses, Cooking Lake aquifer, Cold Lake study area.

Appendix A. (continued)

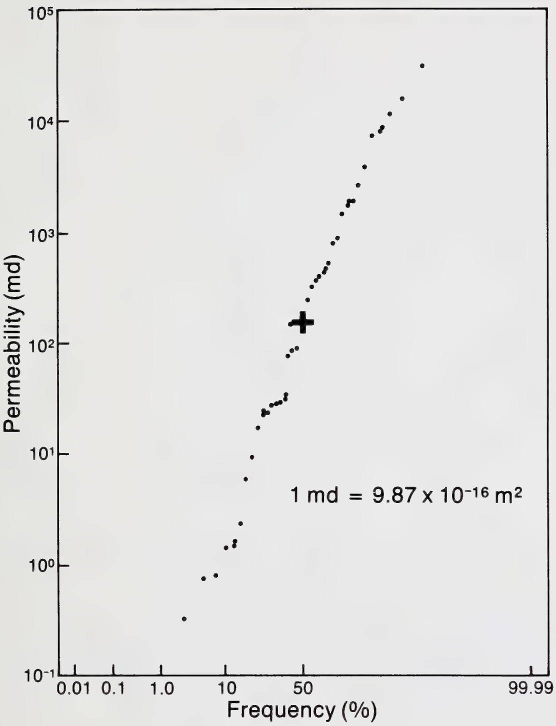

Figure A17. Log-normal cumulative frequency plot for maximum horizontal permeability as derived from core analyses, Camrose Tongue aquifer, Cold Lake study area.

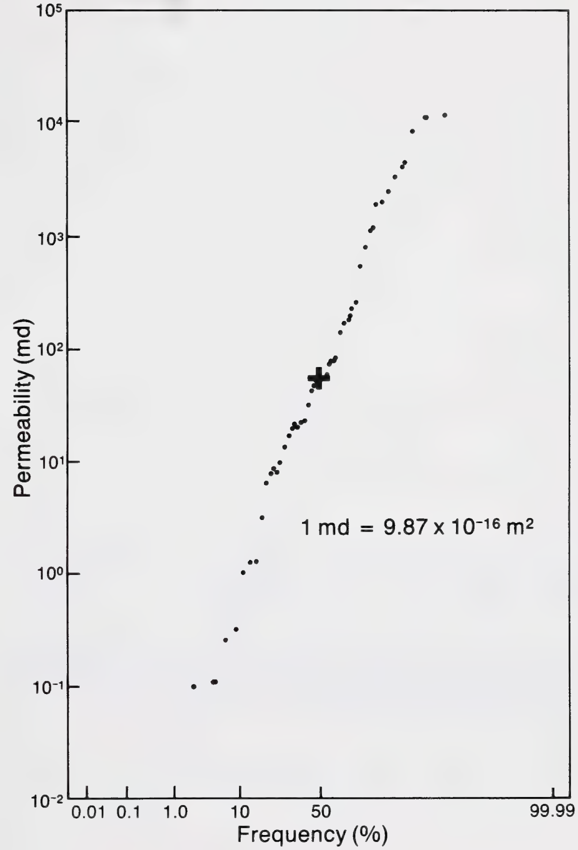

Figure A18. Log-normal cumulative frequency plot for horizontal permeability at 90° with the maximum horizontal as derived from core analyses, Camrose Tongue aquifer, Cold Lake study area.

Appendix A. (continued)

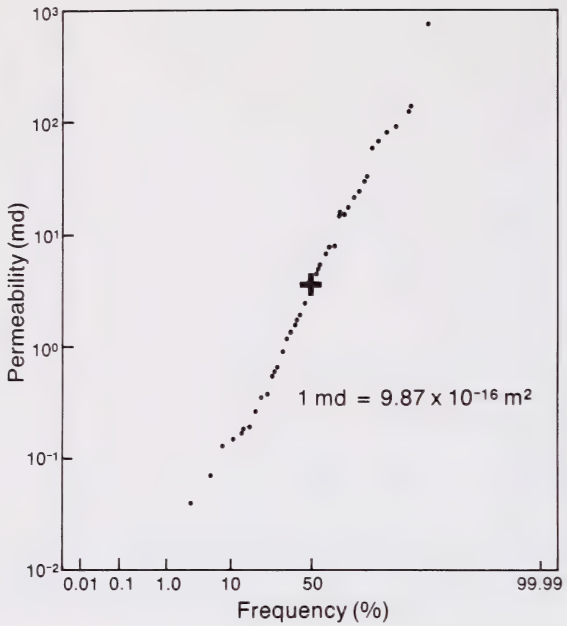

Figure A19. Log-normal cumulative frequency plot for vertical permeability as derived from core analyses, Camrose Tongue aquifer, Cold Lake study area.

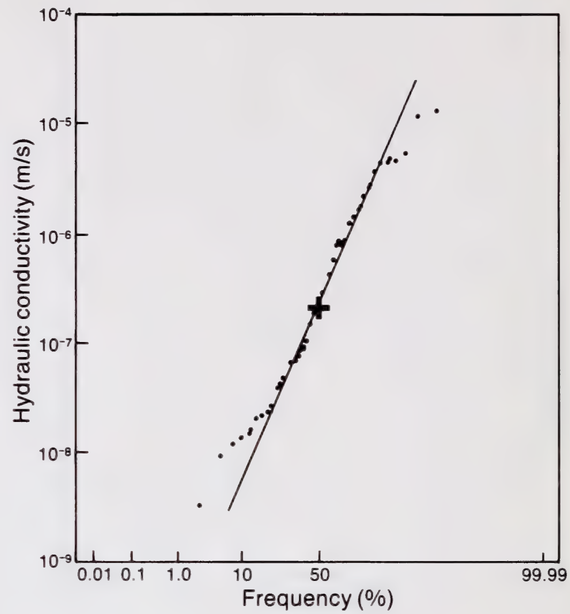

Figure A20. Log-normal cumulative frequency plot for hydraulic conductivity as derived from drillstem tests, Camrose Tongue aquifer, Cold Lake study area.

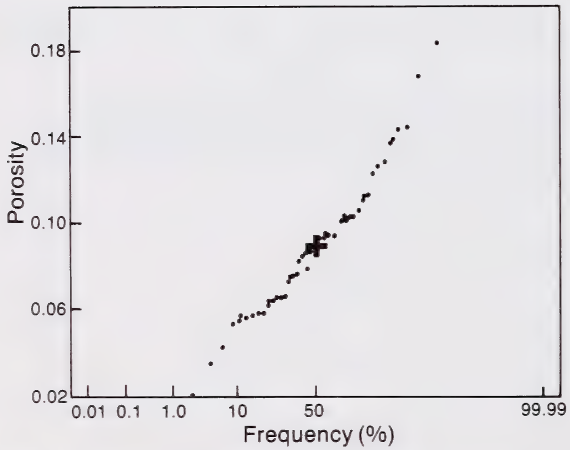

Figure A21. Normal cumulative frequency plot for porosity as derived from core analyses, Camrose Tongue aquifer, Cold Lake study area.

Appendix A. (continued)

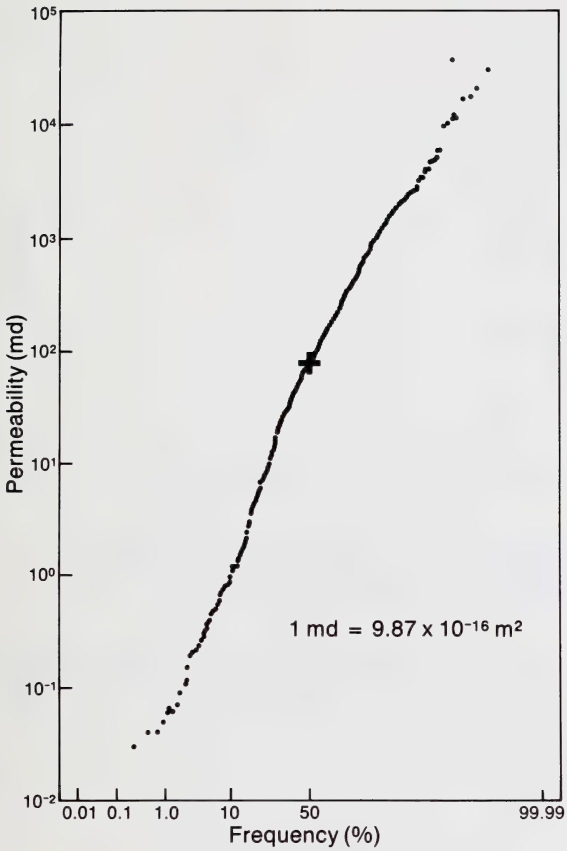

Figure A22. Log-normal cumulative frequency plot for maximum horizontal permeability as derived from core analyses, Grosmont aquifer, Cold Lake study area.

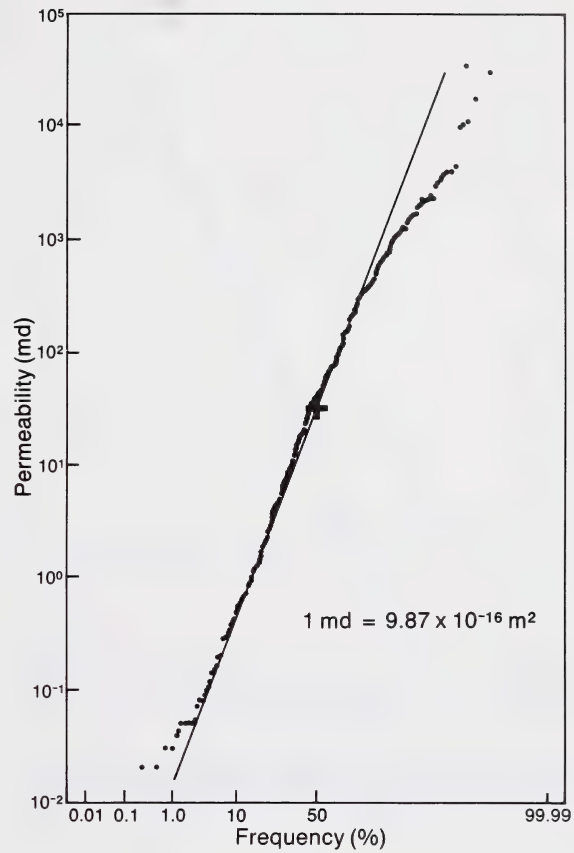

Figure A23. Log-normal cumulative frequency plot for horizontal permeability at 90° with the maximum horizontal as derived from core analyses, Grosmont aquifer, Cold Lake study area.

Appendix A. (continued)

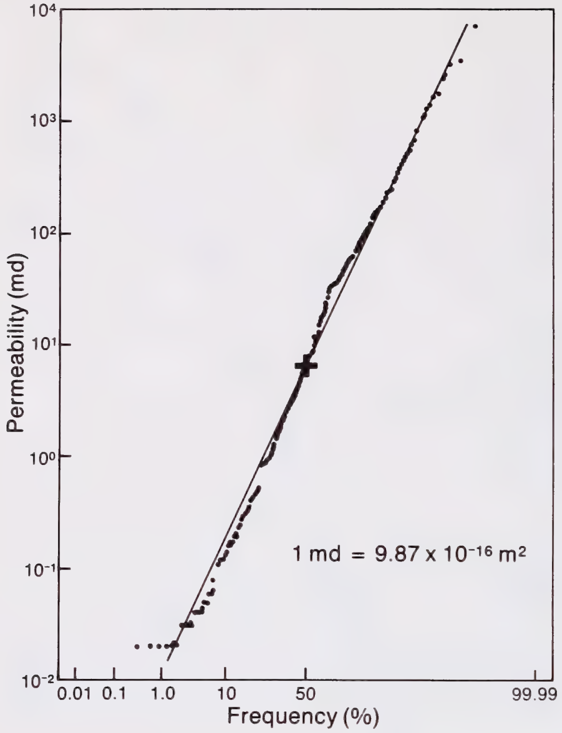

Figure A24. Log-normal cumulative frequency plot for vertical permeability as derived from core analyses, Grosmont aquifer, Cold Lake study area.

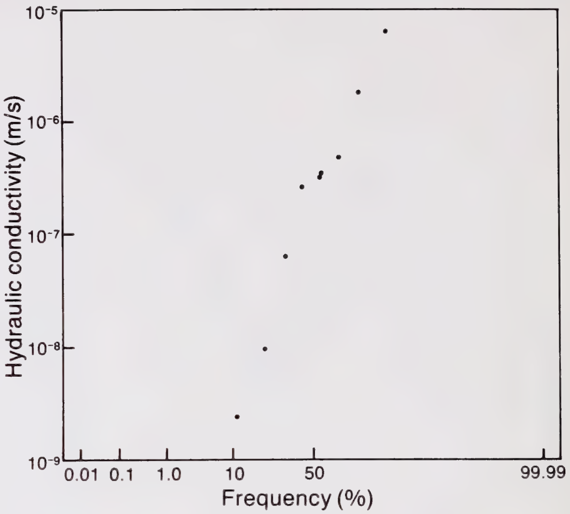

Figure A25. Log-normal cumulative frequency plot for hydraulic conductivity as derived from drillstem tests, Grosmont aquifer, Cold Lake study area.

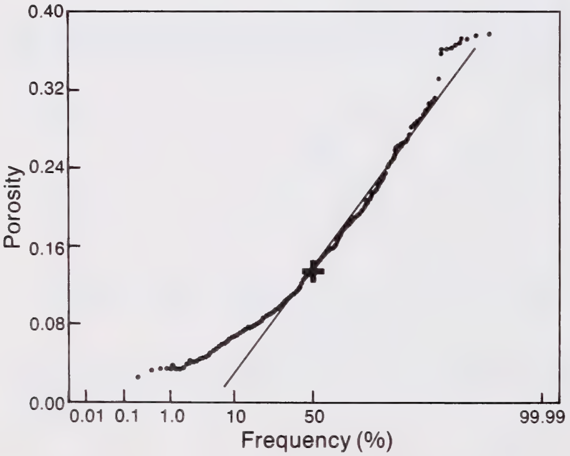

Figure A26. Normal cumulative frequency plot for porosity as derived from core analyses, Grosmont aquifer, Cold Lake study area.

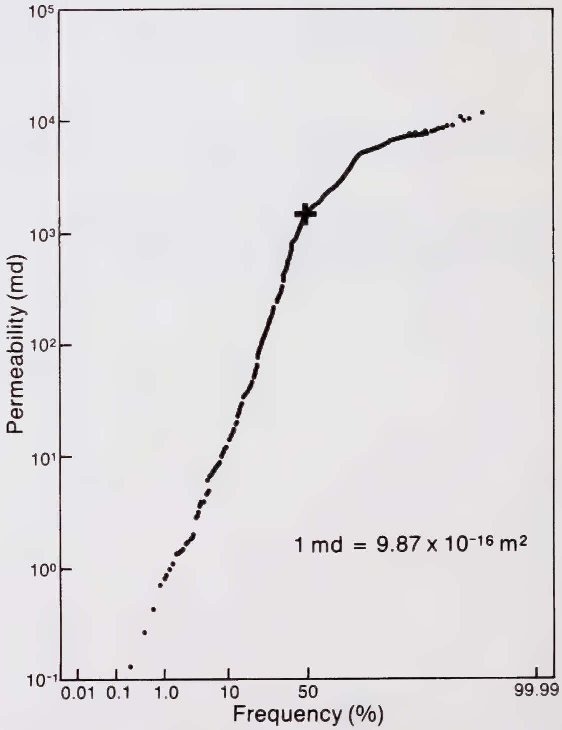

Figure A27. Log-normal cumulative frequency plot for maximum horizontal permeability as derived from core analyses, McMurray aquifer, Cold Lake study area.

Appendix A. (continued)

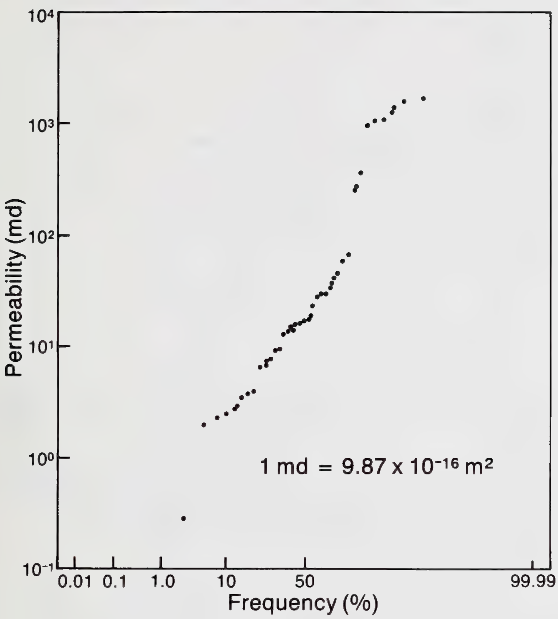

Figure A28. Log-normal cumulative frequency plot for horizontal permeability at 90° with the maximum horizontal as derived from core analyses, McMurray aquifer, Cold Lake study area.

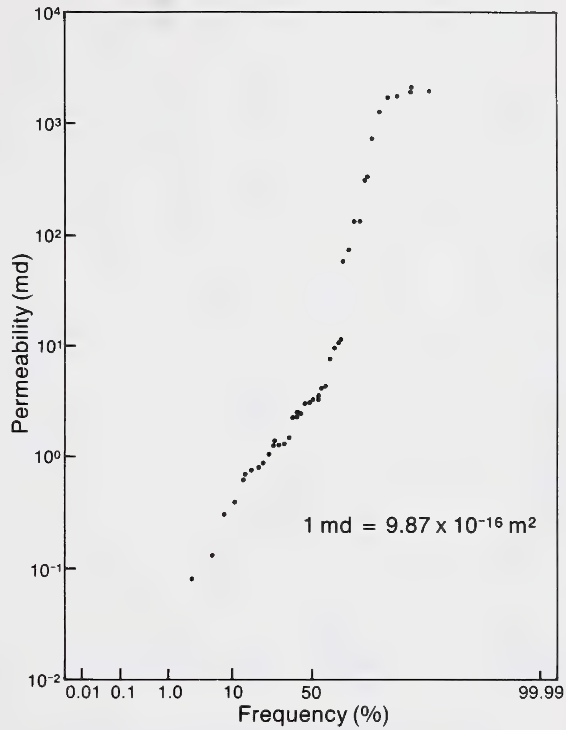

Figure A29. Log-normal cumulative frequency plot for vertical permeability as derived from core analyses, McMurray aquifer, Cold Lake study area.

Appendix A. (continued)

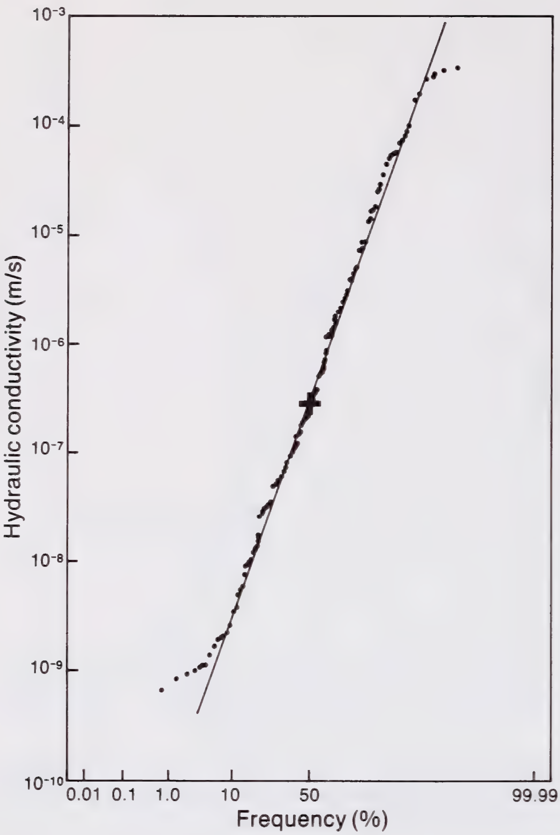

Figure A30. Log-normal cumulative frequency plot for hydraulic conductivity as derived from drillstem tests, McMurray aquifer, Cold Lake study area.

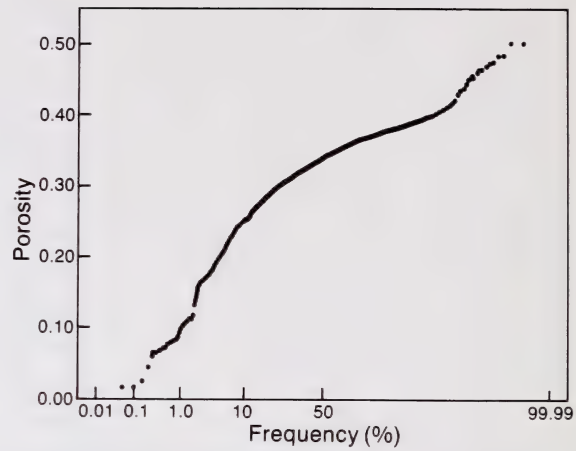

Figure A31. Normal cumulative frequency plot for porosity as derived from core analyses, McMurray aquifer, Cold Lake study area.

Appendix A. (continued)

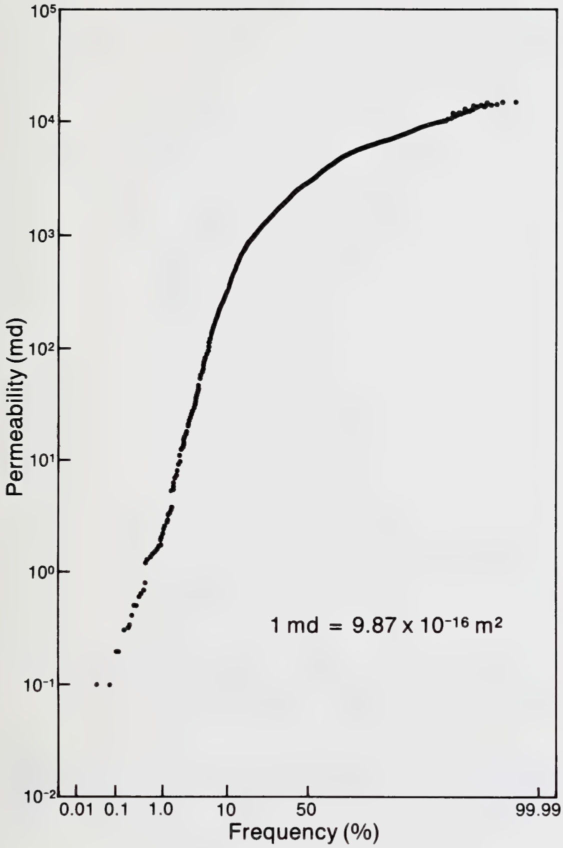

Figure A32. Log-normal cumulative frequency plot for maximum horizontal permeability as derived from core analyses, Clearwater aquifer, Cold Lake study area.

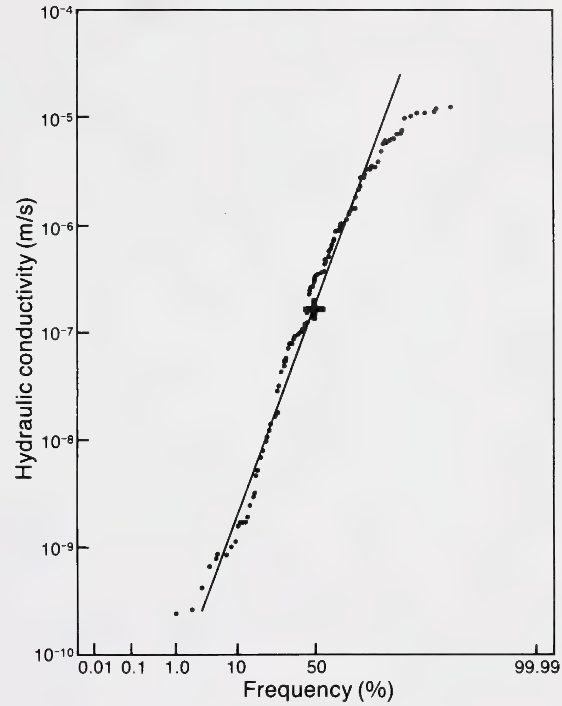

Figure A33. Log-normal cumulative frequency plot for hydraulic conductivity as derived from drillstem tests, Clearwater aquifer, Cold Lake study area.

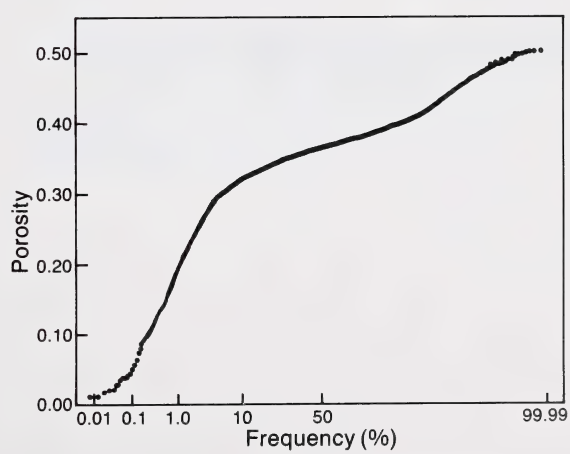

Figure A34. Normal cumulative frequency plot for porosity as derived from core analyses, Clearwater aquifer, Cold Lake study area.

Appendix A. (continued)

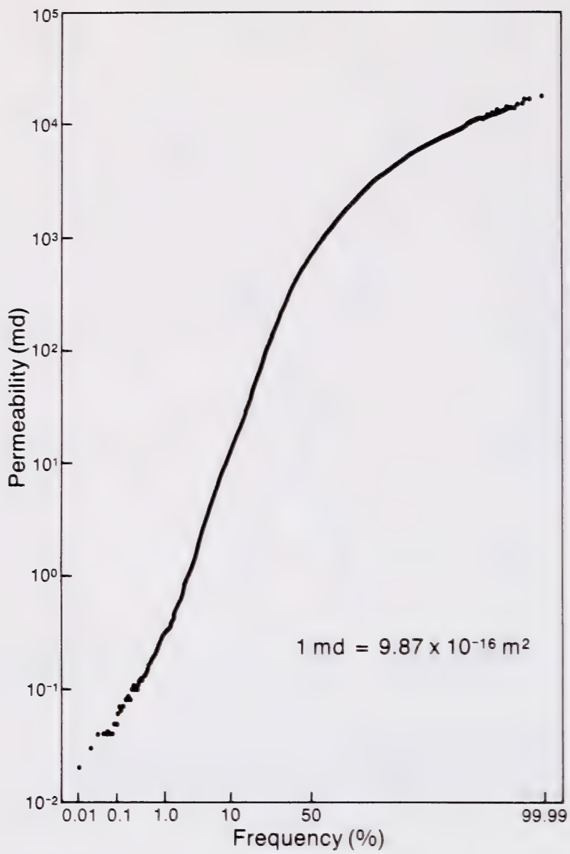

Figure A35. Log-normal cumulative frequency plot for maximum horizontal permeability as derived from core analyses, Mannville aquifer, Cold Lake study area.

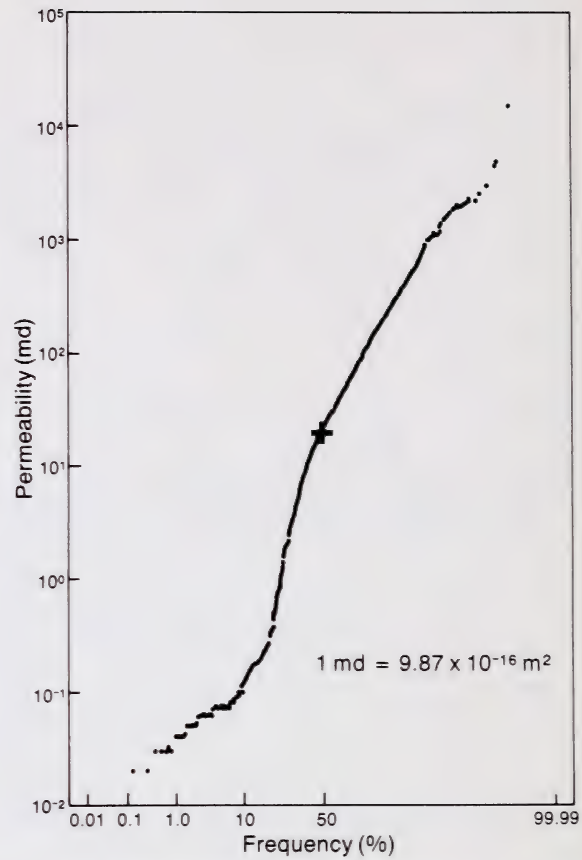

Figure A36. Log-normal cumulative frequency plot for horizontal permeability at 90° with the maximum horizontal as derived from core analyses, Mannville aquifer, Cold Lake study area.

Appendix A. (continued)

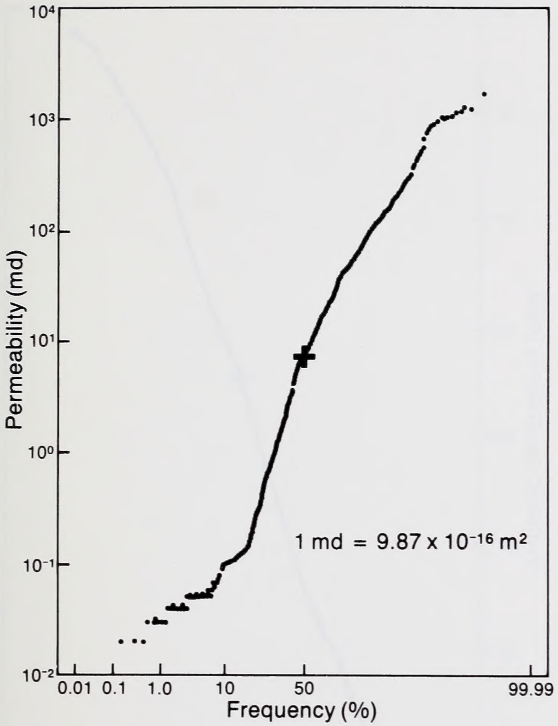

Figure A37. Log-normal cumulative frequency plot for vertical permeability as derived from core analyses, Mannville aquifer, Cold Lake study area.

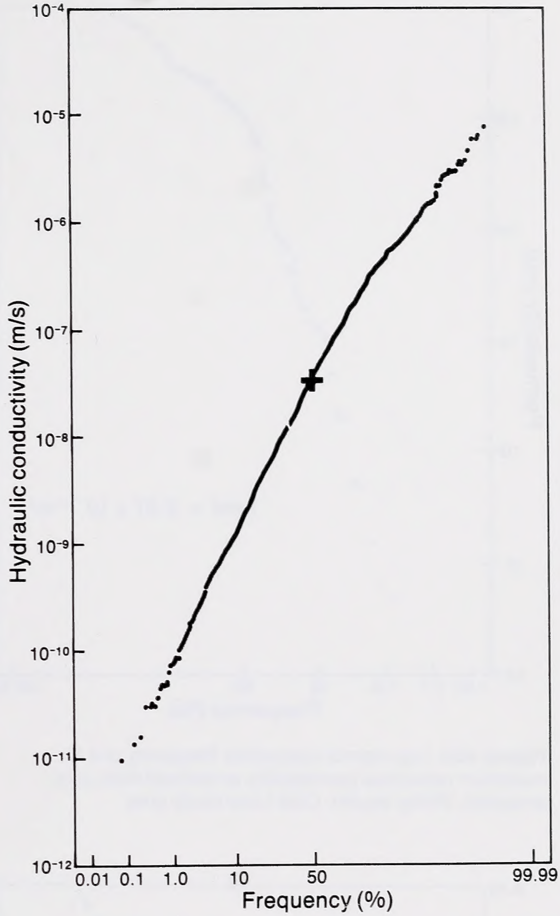

Figure A38. Log-normal cumulative frequency plot for hydraulic conductivity as derived from drillstem tests, Mannville aquifer, Cold Lake study area.

Appendix A. (continued)

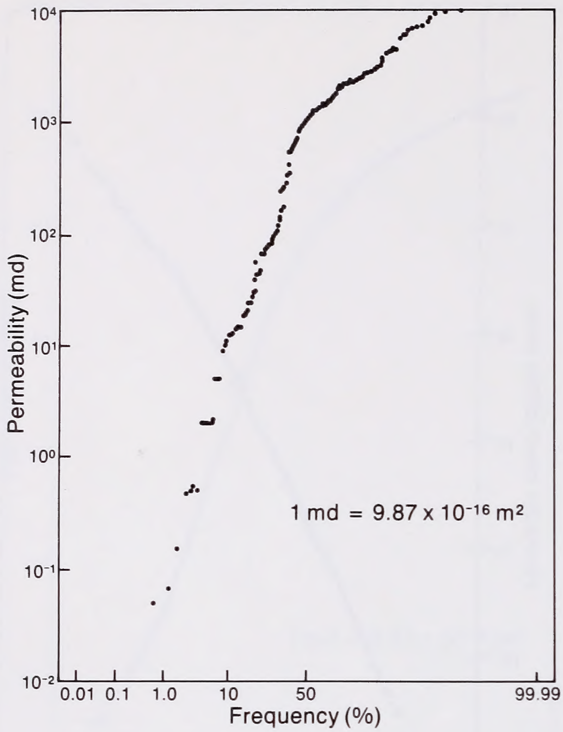

Figure A39. Log-normal cumulative frequency plot for maximum horizontal permeability as derived from core analyses, Viking aquifer, Cold Lake study area.

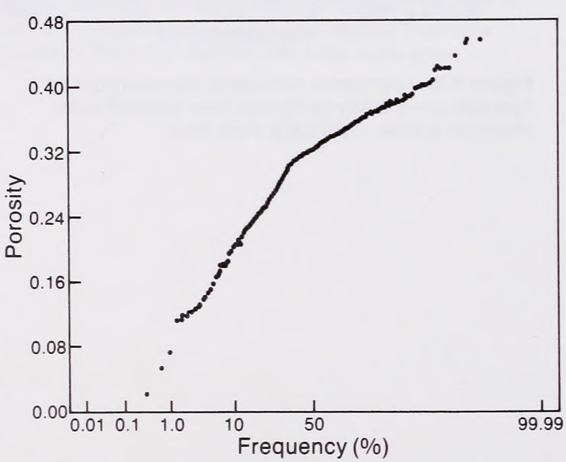

Figure A41. Normal cumulative frequency plot for porosity as derived from core analyses, Viking aquifer, Cold Lake study area.

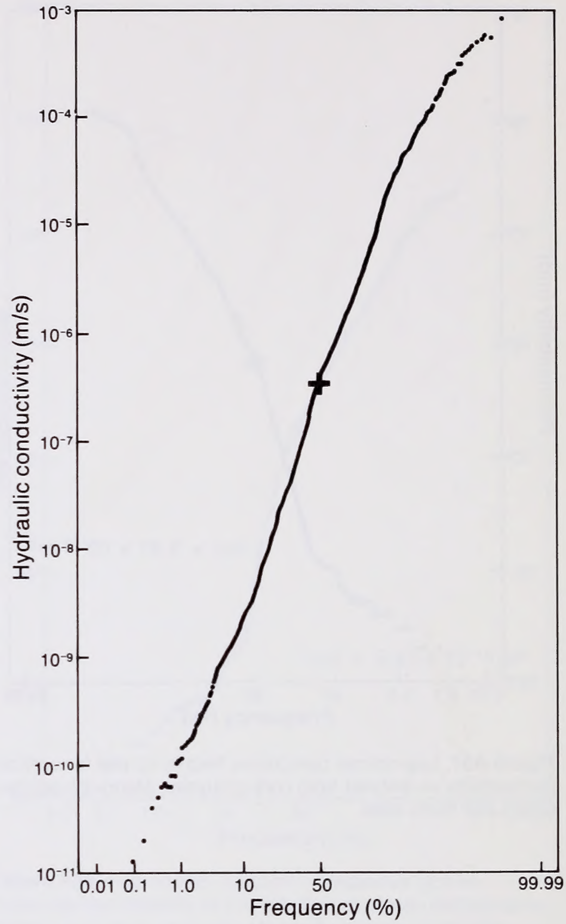

Figure A40. Log-normal cumulative frequency plot for hydraulic conductivity as derived from drillstem tests, Viking aquifer, Cold Lake study area.